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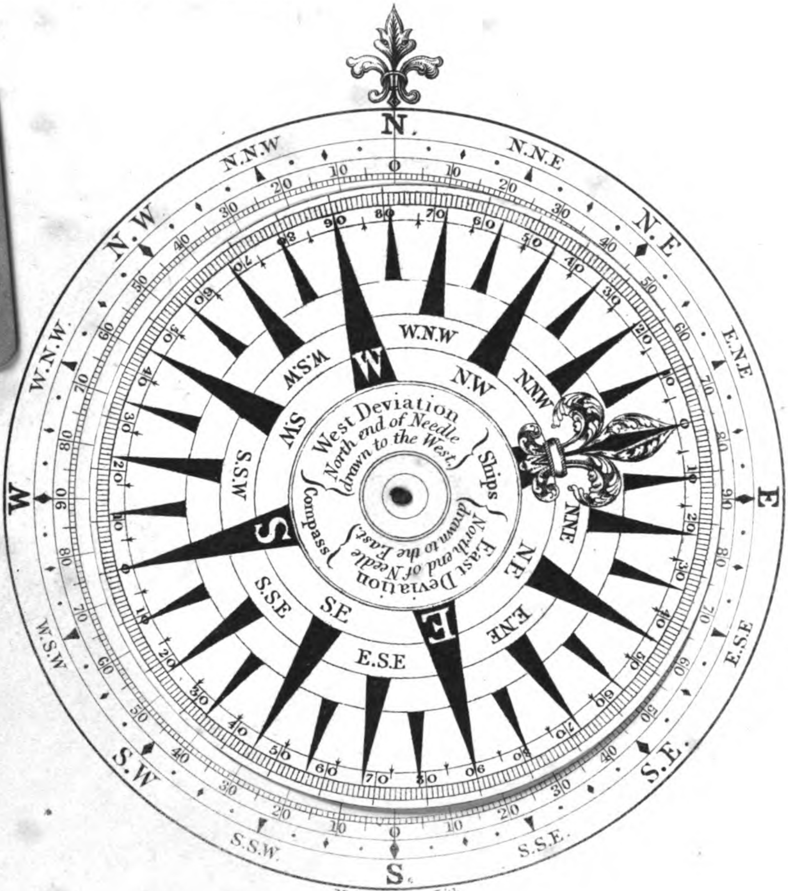
# ELEMENTARY MANUAL.
for the
Deviations of the Compass
in
IRON SHIPS.

System of FIXED and MOVEABLE COMPASS CARDS,
for ascertaining & applying the Deviation of the Compass.

The outer fixed card represents a compass not affected by the iron of the ship;—or the Horizon with the magnetic points and degrees marked on it.

The inner moveable card represents the compass as affected by the iron of the ship; and the Deviation produced is called East or West according as the north point of this compass is drawn to the East or West of the Correct Magnetic North as shewn on the fixed card.



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ELEMENTARY MANUAL

FOR THE

DEVIATIONS OF THE COMPASS IN IRON SHIPS.

ARRANGED IN A SERIES OF QUESTIONS AND ANSWERS,
INTENDED FOR THE USE OF
Seamen, Adjusters of Compasses, and Navigation Schools.

AND

AS AN INTRODUCTION AND COMPANION TO THE
ADMIRALTY MANUAL FOR THE DEVIATIONS OF THE COMPASS.

BY

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MDCCCLXX.

PREFACE.

In bringing a new work on the Deviation of the Compass to the notice of the Naval profession, it is, perhaps, necessary that the writer should offer to the class of readers and students to whom it is specially addressed, a few words of explanation as to its object and method.

It is founded on the Admiralty Manual for the Deviations of the Compass, a work which up to the present time is the only complete theoretical and practical treatise on this important branch of nautical science.

It has long been recognized, and by none more fully than the Editors of that work, that an introductory text-book was wanted, which should convey to the general student or navigator, as much theoretical, combined with practical knowledge, as could be conveyed without requiring the larger amount of physical and mathematical science necessary for an extended use of the Admiralty Manual.

The task of preparing such a work seemed naturally to devolve on the writer, who had been in charge of the Compass Department of Her Majesty's Navy for so many years, and who had besides taken part in the preparation of three successive editions of the Admiralty Manual.

It has, however, been a matter of no slight difficulty and labour. The difficulty is inherent in the subject; for the forces with which we have to deal are not forces of attraction and repulsion of the ordinary kind, but polar forces, the amount and direction of which depend on the action of other magnetic bodies.

It is thus, for the student who has not received an advanced mathematical training, a matter of difficulty—teaching himself by the aid of a book—to obtain any distinct idea of the action of such forces; and to obtain such from a book written in strict scientific order is almost an impossibility. To remove these difficulties is the object of the present work. This, in the writer's opinion, is only to be done by calling the student's attention repeatedly to the reason and meaning of the particular process under review, to cause him to look at the subject from every side, and thus to familiarize his mind with it.

The method of the work it will be seen is that of question and answer. It is hoped that in this way the attention of the reader will be more easily directed to the important parts of the subject, that theoretical explanations will be more easily introduced, and that the knowledge the student acquires will be more readily tested as well by himself as by an examiner; in short, that the elementary manual will, in some degree, supply the place of a tutor.

No pains have been spared to make the work as complete as possible, consistently with the limits which it was necessary to lay down: for that purpose, instructions have been given, not only for the use of the compass as an instrument and for what may be considered the purely practical part of the correction of the deviation, but also the methods in full, with examples for making all the numerical calculations which have been found so useful in studying the magnetism of particular ships; further, giving in each case, such theoretical explanations as will make the meaning of each operation clear, and serve to establish such definite ideas of the distribution of magnetism in the several classes of ships as will prepare and explain to the navigator the changes, or apparent anomalies, which occur either on the voyage or while equipping for sea.

If the writer has in any way succeeded in effecting the objects aimed at, he will be amply rewarded, and will consider that he has discharged at least part of that debt which it is said every man owes to his profession.*

The writer, in conclusion, begs to acknowledge the kind and valuable assistance he has received from Mr. Archibald Smith, F.R.S., in the preparation of his work.

LONDON, *December*, 1870.

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* It has been suggested to me to add here a sentence from Lord Coke's Commentaries: "and albeit the reader shall not at any one day (do what he can) reach to the meaning of our author or of our commentaries, yet let him no way discourage himself, for on some other day, in some other place, that doubt will be cleared."

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ON THE
DEVIATION OF THE COMPASS
IN IRON SHIPS.

SECTION I.

The Compass on board ship.

What important duty, with reference to the compasses, devolves on you on taking charge of the navigation of a ship; and before proceeding to sea?

A. To ascertain from personal examination that the compasses are in good working order, and that they are free from the disturbing influences of moveable iron, or of fixed iron too near the compass; also, that a table of deviations (or the amount of compass error on every course) is furnished for the Standard or navigating compass.

Describe what is necessary to secure the efficient working of a compass.

A. To see that the agate or jewelled caps are free from punctures or cracks; that the points of the pivots are not blunted from over wear, or damaged by concussion; that the card traverses freely in the bowl, and the bowl in its gimbals; that the lubber line of each compass is in a true fore and aft line, and that there is no receptacle for, or any concealed iron within at least six feet that is likely to derange the free working of the compass needles; also, that the needles are sufficiently magnetised and always come up to the same point when disturbed.

What distinction do you draw between a navigating or Standard compass and other compasses?

A. Every ship, other than a coasting vessel, should be fitted with an azimuth compass, to be named the Standard compass; and by it alone should the ship be navigated: all other compasses employed, such as that by the helmsman in steering, that on the bridge or mast by the pilot, that in the cabin as a "tell-tale," are simply to be considered as auxiliaries to the Standard compass.

Are there any special fittings, or arrangements, requisite for the proper working of the Standard compass?

A. There are. It should be placed in the middle line of the ship, and fixed on a permanent and secure pillar or support; raised at such a height as to permit amplitudes of the sun and bearings of the land to be conveniently observed with it over the bulwarks or hammock nettings. It should also be in a position as far removed as possible from any considerable mass of iron—at least 5 feet from iron deck beams—and should not be within 10 feet of the extremity of any elongated iron mass, especially if vertical, such as funnels, stanchions, or the spindle of the wheel: and it should be received as a general rule that no iron, subject to occasional removal, is to be placed within 15 feet of this compass, either on the same deck or on that below it. The Standard compass should further be easily accessible at all times, conveniently near the steering compass, and with suitable provision for its being properly lighted at night; as also for the card being lifted off the pivot when not in use.

In the selection of a Standard compass what are the principal points to be attended to?

A. It should be fitted with an azimuth circle. This circle should be graduated so as to show the angle between the ship's head and any heavenly body, as measured on the horizon, without using the compass card: the sight vanes and reading prism should be so fitted to the azimuth circle as to turn freely in azimuth without moving the compass bowl or disturbing the card; and, generally, as the safety of the ship often depends on the accurate working of this instrument, no reasonable expense should be spared in securing good workmanship in all the details, and nothing should be wasted in showy fittings.

Describe briefly the essential details of an efficient compass.

A. It should be simple in construction, in order that repairs can be made by an ordinary mechanic (the fanciful and complicated arrangements frequently introduced tending to costliness without corresponding efficiency). It should be sensible and at the same time steady in its action: that is, the needle should freely submit to the earth's magnetic force, with power sufficient to steadily obey that force under the varying motions of a ship: it being understood that the apparent steadiness produced by friction or other mechanical impediment is at the expense of accuracy.

To attain this perfect action, the needle should have great directive power with little weight,* and consequently little friction on the point of suspension. The greatest directive power with the smallest weight is obtained by combining two or more flat and thin magnets together—experiments having proved that such a combination of magnets has more actual magnetic power than any single magnet containing the same quantity of steel in mass.

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* See p. 5. Note, On Comparative Merits of Large and Small Compasses.

Two such compound needles attached to a compass card and placed at equal distances from the central line, have many advantages over a single needle :* for, greater directive power is obtained with the same weight; the interference of the pivot cap with the centre of the needle is avoided; the needles can be placed edgeways, thus securing a permanent magnetic axis; and by their ends being placed 60° apart, *i. e.*, 30° on each side the meridian line of the card, an unequal or "wabbling" motion common to single bar compass cards is avoided, and the correction by magnets can be made with much greater accuracy than with a single needle.

The seaman should be also assured that the maker has attended to the several necessary adjustments; notably, that the magnetic axis of the needles coincides with, or is parallel to, the north and south points of the card, that the permanency of their magnetic power may be relied on, that the point of suspension within the bowl is accurately centred, and that the marginal divisions of the compass card are not distorted by shrinking or other causes.

It is desirable that the compass bowl should be constructed of pure copper,† and that the intersecting points of its gimbals should coincide with the point of suspension of the card: also, that the point of suspension of the card should be in the same plane as the upper part of the compass needle.

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* An unfavourable, but incorrect impression still exists against this arrangement, on the grounds that from the similar poles of the needles being so close together, time alone is required to destroy their magnetic power. The writer has had the opportunity of testing two pairs of Admiralty Standard compass cards, each pair having a light and heavy set of needles, that were respectively fifteen and thirteen years in use without repairs: in the first pair there was no appreciable loss—in the latter both had lost about one-twelfth of their original power. A similar pair that had been in use four years, three of which were in an iron ship in tropical Africa, lost respectively one-twenty-fourth and one-sixtieth of their original power.

† This recommendation is based on a now well-known principle in magnetic electricity, namely the influence of non-magnetic substances which are good conductors of electricity in quieting the vibrations of the magnetic needle. Metallic bodies have the greatest influence, silver and copper in a high degree. When a magnet is vibrated within a ring of copper the amplitude of the arcs of vibration are sensibly reduced (although the times of vibration remain the same) and the bar or needle tends rapidly to rest. This is exemplified by the following experiment: an Admiralty Standard compass-card suspended by fibres of silk in a wooden bowl of the same dimensions as its copper bowl, when drawn from the meridian at an angle of 22°, or two points nearly, and allowed to swing, occupied eighteen minutes and made 134 vibrations before the arc was reduced to 2°. When placed in the copper bowl and the experiment repeated, the arc was reduced from 22° to 2° in four minutes, and the number of vibrations reduced to thirty. Pure copper should be employed of substantial thickness for the compass bowl, and the part adjacent to the needle may be increased in solidity by an extra ring—the ends of the needle being permitted to work as close to the ring as may be consistent with freedom of motion.

Great care should have been bestowed by the maker on the pivots and cap: the former, if of steel, should be hardened, duly tempered, and preserved by gilding, or some other process, from rust: the cap should be fitted with a ruby, in preference to an agate*; the cavity for the reception of the pivot point well polished and adapted in shape to the point.†

Finally, it should be seen that the lubber line is vertical, the sight vane perpendicular to the plane of the card, and that the prism admits of adjustment, and can be securely fixed without liability to change of position on being removed for cleaning.

Experience has proved that attention to these several details is essential to the accurate working of the mariner's compass.‡

How far do these observations apply to the steering compasses?

A. Steering compasses being placed according to the requirements of the ship, the moderate and uniform amount of deviation generally attainable at the Standard compass by selection of position, cannot always be secured. Still we should do the best we can, for if, as frequently happens, the steering wheel is placed near an iron stern-post or rudder-head, and further fitted with an iron spindle—near which, of necessity, the steering compass is fixed—then large and perplexing deviations must be expected, defying even approximate correction by magnets; causing much inconvenience to the helmsman, and possibly a total loss of the service of the compass on the ship proceeding into southern latitudes.

The following rules to avoid the inconvenience and even danger just pointed out have been recommended in selecting a position for steering compasses:—"Not to be within half the width of the ship from the stern-post or rudder-head: the spindle of the steering wheel, and the foremost support on which the wheel works *not* to be of iron: avoid vertical iron." The needle should be at least 3 feet 6 inches from iron deck beams; and as much higher as can be made convenient to the helmsman.

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* Agates are often found unequal to withstand pivot action. The ruby is chiefly adopted in the compasses of the Royal Navy under two forms—it is either fitted in the cap for a light card, as described in the text, or fixed in a rounded shape on the head of the pivot to work in a speculum metal cap of a heavy or bad weather card. Sapphires, though more expensive, are not uncommonly used in superior compasses.

† Caps and pivots should be frequently examined at sea—blunted pivots and cracked or perforated caps being at once replaced by perfect ones. It has been well observed that "*compass errors arising from mechanical causes of this kind are often wrongly attributed to changes in the magnetism of the ship.*"—*See Liverpool Compass Committee Reports.*

‡ Such a compass as is here described will probably, in the heavy motion of a ship in a gale of wind, or when subject to the tremulous motion of screw-propelled vessels forced through the water at high rates of speed, as also when in the neighbourhood of heavy guns on firing, be subject to irregular and possibly great vibrations: in such extreme cases, a compass whose card floats in liquid will be found a most useful substitute. In H.M. Ships, two or more are furnished for this service, as also for use in pulling boats. A liquid compass should form part of the equipment of every sea-going ship.

Are there not advocates for navigating iron ships by mast compasses?

A. Yes, but there are objections to the practice. A mast compass is from position not adapted for taking bearings or azimuths of the sun; it cannot be conveniently consulted at night, or during rain and mist, or when the ship has much motion: it is also subject, from the latter cause, to excessive wear and tear tending to rapid deterioration; and in some iron ships it is found to have large errors.

Is there any advantage in having a large number of compasses in a ship?

A. No. Unlike the mean results of a number of chronometers, for example, the mean results of any number of compasses need not necessarily be near the truth; as they may all deviate in one direction, and all be largely in error. Hence the necessity of depending on one compass alone, but that this compass should be in the best position in the ship, of the best manufacture, and the constant attention of the navigator should be devoted to ascertain its errors.

Note. Comparative Merits of Large and Small Compasses.—Of late years much diversity in practice has prevailed as to the size of compasses for use on board ship. The Admiralty Standard Card, for example, is fitted with needles, the maximum lengths of which are 7½ inches, while in large passenger steam vessels the needles are frequently 12 to 15 inches and even longer. The chief object in the employment of large compasses is to enable the helmsman to steer to degrees, and a more accurate course is thus presumed to be preserved.

With reference to this increased size it must be observed, that competent authorities limit the length of efficient compass needles to 5 or 6 inches; beyond this limit an increase of length is alone accompanied by an increase of directive power in the same proportion, and if the thickness of the needle be preserved, the weight, and consequently, the friction, increase in the same ratio. No advantage of directive power is therefore gained by increase of length, but with the increased weight of the card and appendages the increase of friction probably far exceeds the increase of directive force: sluggishness is the result, which is further exaggerated by the extreme slowness of oscillation of long needles compared with short needles.

Large cards, however convenient in practice, are therefore not without danger, for the course steered may deceive the seaman by seeming right to the fraction of a degree, but which avails little if the card itself is wrong half a point and the ship in consequence hazarded. In the opinion of the writer, the present Admiralty Standard Card is as large as should be used for the purposes of *navigation*, and that as regards safety in the long, steady and fast ship, the choice is really between the Admiralty Card and a smaller one. In short, the question may be thus stated: the smaller a card the more correctly it points, the larger a card the more accurately it is read.

SECTION II.

On the deviations of the Compass on board ship, with methods for ascertaining and applying them.

Explain the necessity for a table of deviations for the Standard compass, and the nature of this table.

A. The compasses of every ship are subject to derangement in pointing to the magnetic north: this derangement arises from the iron employed in the ship's construction receiving magnetism from the action of the earth, in obedience to a natural law, and then acting on the compass needle: the resulting error is familiarly known as "the deviation of the compass." The "deviation" differs in amount in different ships, and in different positions in the same ship; the deviations in one ship are, therefore, not generally a guide to the deviations in another ship. It further varies in amount as the ship's head points in various directions, so that there is no security for the faithful performance of a compass, unless its errors from point to point are known and recorded in a table.

But is there not an impression among seamen, that the errors of compasses can be entirely removed by magnet correction, and that a compass so corrected may be considered perfect in practice, and require no further consideration?

A. Unfortunately, such an impression does exist, and with the over-confident it is liable to lead to serious consequences. Compasses are frequently adjusted with great skill, but there must be a favourable combination of circumstances to remove *all* error from a compass, and for it to preserve for even a moderate lapse of time this entire freedom from error. It is, therefore, a necessary precaution, and more especially for a Standard compass, after the most careful correction or adjustment by magnets, to form a table of the residual errors or deviations, and to verify or correct it from time to time.

Why is a table of deviations of more importance for the Standard compass than for the steering or other compasses fitted on board?

A. As before stated, the Standard compass alone should be used to navigate the ship ; the other compasses being considered as useful auxiliaries, or tell-tales : therefore, although it is desirable to know approximately the errors of all auxiliary compasses, still these errors, whatever they may be, do not affect the navigation of the ship ; moreover, the auxiliary compasses being much more liable to change than the Standard, it would be impossible to keep rigidly accurate tables of deviation, and the whole attention of the navigator should, therefore, be devoted to the accuracy of the latter, and by comparison with this the deviation of any other compass may be ascertained at any moment.

Describe the manner in which a table of deviations for the Standard compass is to be obtained by the seaman.

A. This is done by "swinging" the ship, or placing her head on different azimuths, and observing its azimuth by the Standard compass, and also its magnetic azimuth by one or other of the following processes :—

1. Reciprocal bearings ;
2. The bearings of a distant object ;
3. Azimuths and amplitudes of the sun ;

or, these may be combined.

In what cases are the several processes employed ?

A. The first process is convenient when the ship is in a basin, or in a confined and smooth harbour, (free, let it be remembered, from the influences of adjacent iron ships,) and when a suitable position presents itself on the neighbouring shore for fixing a compass, which shall be free from the disturbing influences of iron above or below ground ; such as bollards, gas or water pipes, buried guns or anchors, and volcanic or other rocks, which are known to be magnetic in character. Hawsers to be employed to haul the ship round.

The second process is convenient if the ship be lying in a harbour, or roadstead, with a well defined object—such as a steeple, or high tree, or sharp mountain peak—at such a distance, that the diameter of the space through which the ship swings at her anchor will make no sensible difference in the bearing of the object. [Six to eight miles will generally secure this result.]

In this process, if time will permit, hawsers need not be employed, as the bearing of the distant object can be easily obtained as the ship swings at her anchor to the wind or tide. Or, it may be used at sea, with a lighthouse, an island, or mountain in the remote distance, the ship steaming, or sailing and tacking round an entire circle.

The third process is available under any of the foregoing circumstances, for if we know the exact apparent ship time (or can observe the altitude), the true bearing of the sun is at once found: the difference between the sun's true bearing and its compass bearing (as observed with the ship's head on any particular point of the compass), is the amount of the ship's deviation on that particular point combined with the variation of the compass * due to the geographical locality. We have then only to deduct the latter from the difference of bearings observed to obtain the deviation.

By this process, during the course of a voyage, especially near sunset or sunrise, and with a tranquil sea, a deviation table can be formed by steaming, or tacking and sailing round a circle in the course of half an hour.†

Describe in detail the process by reciprocal bearings.

A. The requisite warps being prepared, the ship is to be gradually swung round, so as to bring her head successively upon each of the thirty-two points of the compass. When the ship is steady, and the compass card steady, and checked from any swing due to the ship's motion, the mutual bearings of the Standard and the shore compass are to be observed by means of a preconcerted signal, and so on from point to point.

To ensure the success of this operation, the two compasses should be distinctly visible from each other with the naked eye; and it will be found convenient in practice for the shore observer to chalk each observation upon a black board, to be read at once from the ship, in order that the observation may be repeated if any apparent inconsistency presents itself.‡

The difference between the correct magnetic bearing of the Standard compass as observed from the shore, and the bearing of the shore compass as observed from the ship, with her head on any particular point,

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* The variation of the compass is the horizontal angle between the compass (undisturbed) north, and the geographical north, or, in other words, the angle between the magnetic and true meridians. It is given on all nautical plans and charts, and is also given in the Admiralty Variation Chart of the World.

† An instructive example of a deviation table for the eight principal points of the compass being obtained for H.M.S. "Malabar," under these conditions, in less than half an hour, is given as an example at p. 12.

‡ When two compasses are employed, it is necessary that they should be compared with each other on shore by the bearing of a distant object. If a second compass is not available, the shore-observer may measure with a theodolite or sextant, at each time of observation from the ship, the angle between the ship's compass (or its position as indicated by a wheft) and some fixed zero point on the shore lying in the same plane: the dropping a flag or ball from the ship indicating the moment the angle is to be measured. Either before or after the operation the ship's Standard compass must be removed to the shore and the *correct* magnetic bearing of the zero point from the shore-observer's position determined. In all simultaneous observations, it will be found useful to check the time of their being made by both observers with previously compared watches.

(with 180° added or subtracted), will show the error on that point which was caused by the ship's iron; in other words, the deviation of the Standard compass according to the direction in which the ship's head was placed.

Describe fully the process by the bearing of a distant object.

A. In this very useful and generally practicable process, the chief aim is the determination of the *correct* magnetic bearing of the selected distant object from the ship; or, in other words, the compass bearing which the distant object would have from on board if the compass were not disturbed by the attraction of the iron. This *correct* bearing may be ascertained in the following ways:—

(a) The Standard compass may be taken to a spot on the adjacent shore (avoiding local influences), from whence the part of the ship where the compass is fixed, and the distant object, shall both be exactly in one line from the observer's eye. The bearing of the object from that point will evidently be the same as its *correct* magnetic bearing from the ship.

(b) The *correct* magnetic bearing of the distant object, will be the mean value of all the observed bearings round the circle, if taken on equi-distant compass points; or of four or more compass bearings, if taken also on equi-distant compass points.

(c) It may be determined by the true, or astronomical bearing of the sun; thus: Observe with the ship's head, steady in any one direction, the Standard compass bearing of the distant object, and of the sun's centre, noting, while observing the latter, the apparent time at ship, or if the horizon be visible, the sun's altitude. With either of these elements, and the latitude of the place, the sun's true bearing is obtained,* and the difference between this and the compass bearing of the sun is the variation of the compass, and the deviation of the ship combined. As the variation of the place is given on the charts, the difference between this variation and the value just determined, leaves the deviation as a quantity to be applied to the observed bearing of the distant object, to get its correct magnetic bearing.

How does the deviation of the compass alter with the ship's course?

A. As the ship makes a complete circle in azimuth, the north end of the needle is drawn sometimes to the right hand of the correct magnetic north, by the attraction of the ship's iron, and sometimes to the left hand; in the former case it is called east deviation, in the latter, west deviation. The employment of these terms, it will be observed, is precisely in the same sense, as we say easterly and westerly variation of the compass.*

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* Azimuth, or Sun's true bearing Tables, computed for intervals of four minutes, by Staff-Commander J. Burdwood, R.N., published by the Admiralty, as also a Time Azimuth Diagram, by Hugh Godfray, M.A., of St. John's College, Cambridge, published by J. D. Potter, 31, Poultry, will be found of great use in practice, as superseding the calculation for the determination of the True Azimuth.

It is known that mistakes frequently occur in practice in the distinction of east and west deviations, by which the effect of the deviation instead of being corrected is doubled; can simple rules be framed to prevent the occurrence of such mistakes?†

A. Were compass cards, that are graduated round the margin in degrees, carried in this graduation from 0 at north round to 360, there would be no difficulty in giving a simple rule; for then, the deviation would be easterly, when the compass bearing from the ship is less than the bearing from the shore, or than the correct magnetic bearing of the distant object; and the deviation would be westerly when the bearings from the ship are greater in value than the bearings from the shore, or the bearing of the distant object: but in the practice of navigation it is considered most advantageous to graduate the card into quadrants, and the above simple rule no longer generally applies. The rule is, however, correct in the first or N. and E. quadrant, and in the third or S. and W. quadrant: the *converse* of the rule (or substituting *less* bearings for *greater*, and *vice versâ*,) is true for the second or E. and S. quadrant, and fourth or W. and N. quadrant: when, however, the bearings happen to lie near the east and west, or the north and south points of the compass, an ambiguity arises, which is embarrassing unless to the well trained observer; and on this account it is desirable, when making arrangements for the construction of a table of deviations, not to select the direction for a shore compass, or for the bearing of a distant object, which shall lie near a cardinal point.

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* In a region where the compass north is drawn to the right of the true north, or direction of the geographical North pole of the earth, it is known as Easterly variation; where drawn to the left, as in Great Britain, as Westerly variation.

† The student is here referred to the system of fixed and moveable compass-cards placed within the opening cover of the book, an arrangement which will prevent any mistake of this kind. By simply placing the bearing by ship's compass on the moveable card, against the correct bearing as obtained by the compass on shore (*reversed*), or by the correct magnetic bearing of the distant object, or as determined by the sun, on the fixed card, the direction in which the north end of the ship's compass-needle is drawn, whether to east or west, will be evident at sight.

How do you arrange tabular forms for finding the deviation by the several processes described?

A. In the following manner:—

1. By reciprocal bearings.

H.M.S. Trident. Greenhithe, River Thames, 23*rd December,* 1856.

Time.*	Ship's Head by the Standard Compass.	Simultaneous Bearings.		Deviation of Standard Compass.
		From Standard Compass on board.	From the Shore Compass.	
h. m.		° ′	° ′	° ′
9 10 a.m.	North.	S. 37 50 E.	N. 41 0 W.	3 10 W.
9 14 "	N. by E.	S. 45 0 E.	N. 42 25 W.	2 35 E.
9 17 "	N.N.E.	S. 51 40 E.	N. 43 30 W.	8 10 E.
9 21 "	N.E. by N.	S. 57 20 E.	N. 44 10 W.	13 10 E.
9 26 "	N.E.	S. 61 50 E.	N. 45 0 W.	16 50 E.
9 32 "	N.E. by E.	S. 65 30 E.	N. 46 0 W.	19 30 E.
And similarly at all points of the Compass.				

* The time—as taken by compared watches—may be omitted if the shore observations can be clearly made out by being chalked on a black board.

2. By bearing of a distant object.

H.M.S. Trident. Greenhithe, River Thames, 24*th December,* 1856.

Correct magnetic bearing of distant object from ship. Severndroog Tower, N. 63° 0′ W., distant 11 miles.

Ship's Head by the Standard Compass.	Bearing of distant object by the Standard Compass.	Deviation of Standard Compass.
	° ′	° ′
East.	N. 83 20 W.	20 20 E.
E. by S.	N. 82 15 W.	19 15 E.
E.S.E.	N. 81 5 W.	18 5 E.
S.E. by E.	N. 79 30 W.	16 30 E.
S.E.	N. 77 40 W.	14 40 E.
And similarly at all points of the Compass.		

3. By azimuths of the sun.

H.M.S. Malabar. At Sea in Lat. 12° 30′ *N., Long.* 44° 0′ E.
January 10*th*, 1870. *Ship being slowly steamed round the circle.*

Ship's Hd. by the Standard Compass.	Apparent Time at Ship.	Bearing of ☉' Centre.		Variation observed in Ship.	Variation by Chart at Ship's place.	Deviation of Standard Compass.
		True.	Magnetic.			
		° ′	° ′	° ′	° ′	° ′
N.W.	Rising Amplitude.	S. 67 30 E.	S. 59 0 E.	8 30 W.	3 30 W.	5 0 W.
North	VI^h 20 a.m.	67 30	63 40	3 50 W.	...	0 20 W.
N.E.	„ 23	67 20	68 30	1 10 E.	...	4 40 E.
East.	„ 26½	67 10	62 30	4 40 W.	...	1 10 W.
S.E.	„ 28½	67 0	56 30	10 30 W.	...	7 0 W.
South.	„ 30½	66 55	59 50	7 5 W.	...	3 35 W.
S.W.	„ 33	66 45	66 0	0 45 W.	...	2 45 E.
West.	„ 40	66 20	61 30	4 50 W.	...	1 20 W.

For what purposes is a table of deviations so formed to be used?

A. 1st. To correct the course steered by the compass, in order that the correct magnetic course actually made good may be used in the calculation of the ship's reckoning, or to lay it down on the chart.

2nd. If one or more bearings of the land are taken, to correct these bearings by the amount of deviation due to the direction of the ship's head at the time.

3rd. If we wish to shape a course for a port, and having either by calculation, or as taken from the chart, the correct magnetic course to be made good, so to apply the deviation as to obtain the compass course to be steered.

How do you apply the deviation in these three cases?

A. In the first case, the deviation for the given compass course is applied to the *right* or *left* of the compass course steered, according as the deviation is *east* or *west*, to obtain the correct magnetic course made good: for example, if steering N.E. by compass, and the deviation for that point is 16° 50′ E., the ship is actually steering by chart N. 61° 50′ E. (magnetic), or N.E. by E. ½.E.: or, if steering S.E., and with a deviation of 14° 40′ E. for that point, she is steering by chart S. 30° 20′ E. (magnetic), or nearly S.S.E. ¾ E.*

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* This is immediately seen by the use of the fixed and moveable compass-cards within the opening cover of the book.

2nd. To correct bearings,—we have to apply the deviation due to the ship's compass course at the time they are taken: East deviation to the right hand, West deviation to the left hand. For example: there are two islands bearing S.E. and W.S.W.; the ship's head is N.E., on which point there is 10° east deviation; the correct magnetic bearings of the islands will be respectively, S. 35° E., and S. 77° 30′ W.*

In the third case; *and this is important to remember*, not only is the general rule of applying the deviation *reversed*, but the correction to be applied is the deviation due to the given magnetic course, not that due to a compass course, as in case 1: that is, to the correct magnetic course as found from the chart, or by calculation; the deviation, as due to that course, must be applied to the *left* if Easterly, and to the right if Westerly, in order to find the course to be *steered* by compass *approximately*: for example; the correct magnetic course to a port (from the chart) is N. 56° E.; the deviation on that point is 19° E.; the ship, therefore, must be steered *near* a N. 37° E. course by compass. It will be observed that on those courses near which the deviation is considerable and rapidly changing, the deviation on a given magnetic course is considerably different from that on the compass course of the same name. This sometimes causes perplexity, and even error, so that to prevent the possibility of error in such an important operation as shaping a course, a steering table should be prepared from the deviation table, wherein the corrections have been applied conversely,† and kept ready for immediate use.‡

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* Or, by fixed and moveable cards; place the moveable card to 10° easterly deviation, and at the coincidence of the two bearings S.E. and W.S.W. on it, with the fixed card, will be the correct bearings.

† See page 23, where such a table is easily prepared by the aid of Napier's graphic method: and is more accurate and simple than using the fixed and moveable compass cards.

‡ If the deviations are small, the fixed and moveable cards can be advantageously used to obtain the compass course, but if the deviations are large and change rapidly on some points, finding the compass course is then less simple. It must be performed in the following manner:—

By fixed and moveable cards, *to shape or steer a course by compass.*

1. Place the moveable card for the amount of deviation due to the *correct magnetic course* and note the ship's compass course coincident with the course on the fixed card.
2. Place the moveable card for the amount of deviation due to the point just found —note the point on moveable card coincident with the required course on fixed card.
3. Now place the moveable card for the deviation due to the mean of the two points just noted, the point of coincidence with the required course on fixed card in the *compass course* to be steered.

Note. When the deviations are small in amount the first process will be sufficient.

What is the general character of the deviation tables of various classes of ships, both wood and iron built?

A. In wood-built sailing ships, with the compass in the general position on the quarter-deck, the points of *no* deviation are usually when the ship's head is at or very near the north and south points; and the points of maximum deviation at or about east and west, by compass: Easterly deviation when the ship's head is in the eastern semicircle; Westerly deviation when in the western semicircle. In wood-built steam vessels with the compass aft, there is the same general character, but the points of no deviation often lie several degrees on either side of the north and south points, and the points of maximum deviation similarly lie several degrees on either side the east and west points.

Iron-built ships differ in these respects materially from wood-built ships, as each iron vessel has a distinctive character of her own. The direction of the points of *no* deviation, instead of being near the north and south points of the compass, are chiefly dependent on the direction (by compass) of the ship's head and keel while building, and are generally nearly in that direction; they are not, however, always opposite to each other, nor are the points of maximum deviation at right angles to the points of no deviation, as usually obtains in wood-built ships.*

Are the deviations subject to change when the ship changes her geographical position?

A. According to theory, changes of the deviation must take place on every change of the ship's geographical position, provided there is a change in either the magnetic dip or the horizontal force of the earth, and therefore particularly on a change of latitude; this is the result of general laws connected with the magnetism of the earth. Experience confirms the theoretical conclusions, for we find that the deviations of the wood sailing-ship are entirely reversed in direction in the southern hemisphere (the points of no deviation remaining the same). The deviations of a wood vessel fitted with steam machinery, although not always subject to the entire reversal of the deviations in the southern hemisphere, are still considerably changed and generally reduced; while the changes in the deviation of the iron-built vessel depend materially on the good or bad position of the compass. In a properly placed compass the changes are far less in proportion than the changes in wood-built ships; but in an improper position the changes, especially when the original deviations in England were large, may be exaggerated, so as to render the compass useless.

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* Vessels constructed partly of wood and partly of iron, known as "composite built," have in recent years been widely introduced into both the Royal and mercantile navies. These vessels may be divided into two classes, one in which the beams, vertical supports or stanchions, and the deck stringers, entirely are iron, and the hull wood; the other class, in addition, have the ribs and bracings of the hull iron. Both classes conform in magnetic character more nearly to the iron-built than to the wood-built ship—the latter class with iron ribs in a very marked degree.

What is involved in the terms "good" and "bad" positions, as applied to the compass in iron ships?

A. It is impossible in an iron ship to avoid the influence on the compass of the magnetic force necessarily developed in such a great mass of iron: this in itself may be sufficiently formidable in its effects even on a compass favourably placed in an elevated position, and clear of the influence of individual masses of iron having magnetism independent of the entire hull of the ship. We see this latter precaution, however, frequently neglected, and compasses placed near the iron rudder-head, or close to the iron axle or the upright of the steering wheel; the result being that on the ship reaching high south latitudes they become useless. Compasses under these conditions are unquestionably improperly placed.*

Is it the duty of the seaman in the course of his voyage to watch from day to day the deviation of the compass, and to determine the changes which take place?

A. Such, doubtless, is his duty, and it is easily discharged; as by occasionally observing a few azimuths with the ship's head on different courses, and comparing the variation so determined, with that of the known variation of the place, the change of deviation may be ascertained, and the means afforded for the construction of new tables, or for adjusting the old one.

Is the duty of the seaman the same when correcting magnets are applied to compasses?

A. Yes. Magnets are necessarily employed to reduce the very large deviations occasionally found in iron ships: † the compass, however, so corrected, can never be considered as entirely free from errors, and the deviations must be expected to change on change of latitude.

Are the errors the same, or different, as the ship heels over?

A. In wood-built vessels the compass errors arising from heeling are scarcely appreciable, and the table of deviations found with the ship upright may be confidently used; but in iron-built vessels the case is different. Experience has proved that in them, in many cases, serious errors, due alone to the heeling over of the ship, exist.

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* It was from the reports of seamen bewildered by the action of compasses placed as thus described that the subject, in the early introduction of iron ships, was for a long time embarrassed; and induced a general belief that the laws affecting the deviation were capricious, and of the nature to baffle investigation.

† Or rather for this, which is really most important, to equalize the directive force on different azimuths. (See Section XI. p. 108.)

Does the heeling error depend on the direction of the ship's head?

A. It does. For whenever the ship's head is at, or near, east or west by the disturbed compass, the heeling error at that compass vanishes; but with the ship's head at, or near, North and South, the heeling error is at its *maximum.* We are warned, therefore, by the knowledge of this law, to be watchful when the iron ship's head is in a meridional direction, and to embrace that opportunity of practically testing the amount of error as the ship changes the amount of heel, by repeated observation.

In what direction is the compass needle disturbed as the iron ship heels over?

A. In the majority of iron ships, the north end of the compass needle is drawn to windward: but it is to be observed that this is only while the ship is in the northern hemisphere; and in compasses above the upper deck.

How does this additional compass disturbance of the north end of the needle being drawn to windward, affect the navigation of a ship?

A. If the ship be kept steady on one compass course, she will be found to windward of her supposed position when on northerly courses; and to leeward on southerly courses. If she be steered steadily for a fixed point on the horizon, she will then *appear* to fall off as she heels on northerly courses, and to come up on southerly. It follows that, in steering by compass and wishing to make a *straight course,* we must keep away, by compass, on either tack, as the ship heels, when on northerly courses, and keep closer to the wind, by compass, on either tack, when on southerly courses.

What is the effect in the few iron ships in which the compass needle is drawn to leeward?

A. The reverse; and further it must be recollected, that in the southern hemisphere, the effect may be reversed in both cases:—*i. e.,* ships which have the north end of the needle drawn to windward in the northern hemisphere, will, especially in high south latitudes, have it drawn sensibly to leeward, and *vice-versâ.*

SECTION III.

Napier's diagram, and curve of deviation—Exact method of applying the deviations to a ship's courses—Formation of steering table.

It is frequently found useful in various branches of astronomical and physical science to represent complex tables of numbers by means of curve lines, and thus to picture to the eye relations or laws concealed within the numbers of the table: these modes of representation are commonly known as "graphic methods." Are you aware of any such method being applied to a table of deviations?

A. Yes; there is one well adapted for this purpose known as Napier's.* It is a diagram easily constructed and easily applied, and requires no theoretical knowledge. It has the great advantage of giving from observations made on a small number of points of the compass, or on points at irregular intervals, the deviations on every point corrected as far as possible for errors of observation; and, on the other hand, if a great number of observations are made also on various azimuths of the ship's head at irregular intervals, it enables us to obtain the most probable value of the deviation on any point of the compass from them.

Then this method must be peculiarly adapted to cases where, from the ship swinging round at her anchorage to the winds or in a tide-way, the deviation must be observed at irregular periods, and not necessarily on exact points of the compass, or on equidistant points; and also when tacking or steaming round a circle at sea as previously described?

A. Under these several conditions, and indeed generally in any investigation connected with the magnetism of ships, Napier's diagram is of great value; and it is a matter of surprise that its uses are not more generally known; for, in addition to what has been described, the diagram with the curve of deviations drawn affords a convenient and *exact* method of applying the deviations to the ship's courses—whether we wish to convert compass courses into correct magnetic courses, or, having the correct given magnetic course, to find the *exact* corresponding compass course.

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* Due to Mr. J. R. Napier, F.R.S. Graphic methods for correcting the ship's course for the deviation of the compass have also been designed by Rear-Admiral Ryder, Mr. Archibald Smith, F.R.S., and Mr. W. W. Rundell. Admiral Ryder's, which is an extension of Napier's diagram, is published by the Admiralty. Mr. Smith's, known as the straight line method, is published by the Board of Trade, and also furnished to H.M. Ships for Fleet tactics, for which it is well adapted. Mr. Rundell's is known as the circular method. They are all useful in practice.

Describe the construction of the diagram.

A. The diagram may be considered as representing the margin of a compass card cut at the north point and straightened into a vertical line. This vertical line may be drawn of any convenient length,* and divided into 32 equal parts, representing the 32 points of the compass, commencing at the top with north, and ranged in the order of N. by E., N.N.E., &c. The vertical line is then intersected at each of the 32 points by two straight lines inclined to it at an angle of 60°: one of these is drawn as a plain line, and one as a dotted line—the dotted line being that inclined from the horizontal or dipping, to the right hand.

The vertical line is further divided into 360° from 0° or north, at the top, to 360° at the bottom, and again similarly to ordinary compass cards from 0° at north and south, to 90° at east and west.

How are the observed deviations laid down on the diagram, in order to construct a curve of deviations?

A. As follows: Easterly deviations are laid down to the right of the vertical line, Westerly deviations to the left. The plain and dotted lines forming equilateral triangles with the central line; the scale on each is the same, and the amount of the deviation may therefore be taken from the vertical scale of degrees: then, if the deviation has been determined with the ship's head on an exact compass point, lay down the deviation on the *dotted* line passing through that point; but if not observed on the exact point, then on a line drawn parallel to the *dotted* line, the compass course or direction of ship's head being still taken from the vertical line. Mark the point of deviation with a dot or cross, and when all the deviations are completed, draw with a pencil a flowing curve passing as nearly as possible through all the dots or crosses. When satisfied with the curve in pencil (or that each observation is fairly represented in the curve or is so erroneous that it ought to be rejected—a matter which is readily estimated by the eye), draw the curve in ink.

Are the deviations in any case laid down on the plain lines?

A. On the rare occasions when the table of deviations is given for the *correct* magnetic course or direction of the ship's head, the plain line is used instead of the dotted.*

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* In the diagram published by the Admiralty, the vertical line is 18 inches in length; a convenient size in practice, but it should not be smaller. See Plate I., page 21.

What is the smallest number of observed deviations available for obtaining a complete curve of deviations?

A. It is possible if the deviations have been observed accurately, at or near the four inter-cardinal or quadrantal points of N.E., S.E., S.W., and N.W., to form a fairly approximate curve: if the deviations have been observed at or near the eight principal points, a curve can then be drawn which will give the deviation on every point of the compass within very small limits of error.

Exact method of applying the deviations to a ship's courses.

You have stated that Napier's diagram, with the curve of deviations completed, affords a convenient and exact method of applying the deviation to the ship's courses. How is this performed?

A. The correction of the deviation may be required as follows:—

1st. From the compass course which has been steered—to find the magnetic course to be laid down on the chart;

2nd. From the magnetic course given by the chart—to find the compass course on which the ship's head ought to be kept.

For the first. On the vertical line take the given compass course. Move in a direction parallel to the *dotted* lines till you arrive at the curve, and then move in a direction parallel to the *plain* lines till you get back to the vertical line. The point on the vertical line at which you arrive is the magnetic course required.

Example.—If in H.M.S. Achilles, the Standard compass course is N.E. by N., follow the *dotted* line of that rhumb till it meets the curve, and then returning to the vertical line in a direction parallel to the *plain* line; it will be found to intersect it at N.E. by E., which is the magnetic course to be laid down on the chart.

Again, the Achilles is steering N. 60° W. by the Standard compass. What magnetic course is she making in order to place it on the chart?—Answer, N. 81° W.

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* It is, however, now generally understood that this procedure is contrary to practice and may lead to error.

For the second. On the vertical line take the given magnetic course. Move in a direction parallel to the *plain* lines till you arrive at the curve, and then move in a direction parallel to the *dotted* lines till you get back to the vertical line. The point on the vertical line at which you arrive is the compass course required.

Example.—If in H.M.S. Achilles the magnetic course required be N.W. by N., follow the *plain* line of that rhumb till it meets the curve, and then returning to the vertical line in a direction parallel to the *dotted* line; it will be found to intersect at N.N.W., the required course by Standard compass.

Again, it is found from the chart that the magnetic course from the noon position of the Achilles to the Start point is N. 86° E. What course must be steered by Standard compass?—Answer, N. 61½° E., or nearly N.E. by E. ½ E.

Note.—Napier's diagram will be found of great use when, in swinging a ship, we wish to construct deviation tables for any number of compasses placed in different parts of the vessel. The process is as follows:—

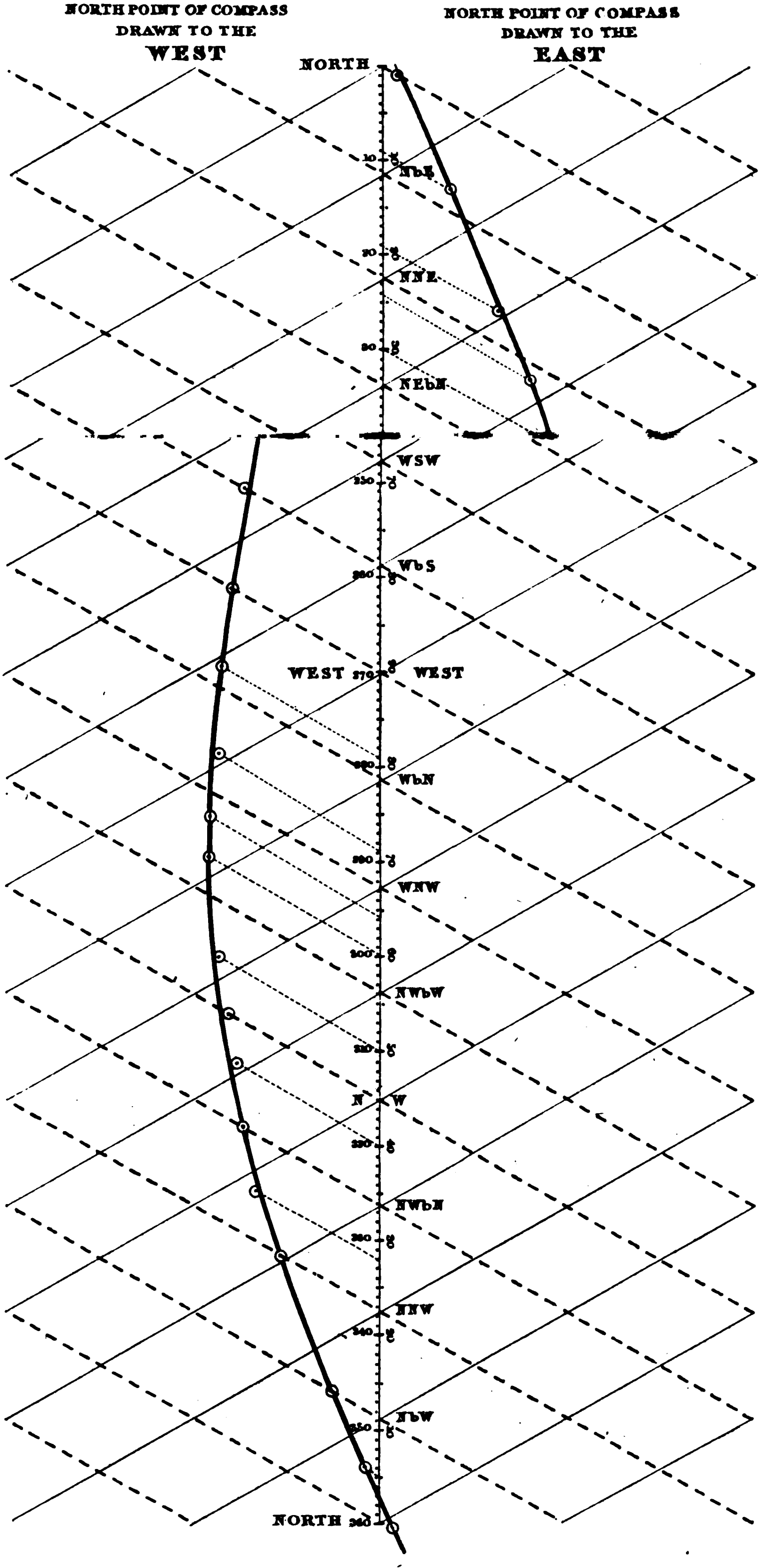
At the time of observing the deviation of the Standard compass, note *very exactly* the azimuth of the ship's head by it, and, through a preconcerted signal, also the azimuth of the ship's head by the other compasses with equal exactness; and so on through the swinging of the ship.

Then the azimuth of the ship's head *correct magnetic* being known at each observation made by the Standard compass, the difference between this and the ship's head as observed by each compass gives of course their deviations respectively. These several deviations for each compass being then laid down on Napier's diagram, and the curve drawn, a table for the 32 points is obtained.

Plate I.
(to face page 21)

NAPIER'S DIAGRAM

With curve of deviations for Standard Compass H.M.S. Achilles, Sheerness Octr. 1864.



Construct, now, a curve* of deviations for the Standard compass of H.M.S. Achilles, using for the purpose the following observations made at Sheerness on October 12th and 13th, 1864:—

	Ship's Head by the Standard Compass.	Simultaneous Bearings.		Deviation of the Standard Compass.
		From Standard Compass on board.	From the Shore Compass.	
	°	° ′	° ′	° ′
October 12th	N. 71½ W.	S. 83 20 E.	S. 76 40 W.	20 0 W.
	- 64½ -	84 0	75 10	20 50 W.
	- 60 -	84 10	74 50	21 0 W.
	- 50 -	86 50	73 20	19 50 W.
	N. W.	88 30	72 50	18 40 W.
	N. 40 W.	N. 89 20 E.	71 40	17 40 W.
	N.W. by N.	87 50	71 0	16 50 W.
	N. 28 W.	85 10	70 0	15 10 W.
	N.N.W.	82 0	70 0	12 0 W.
	N. by W.	76 0	69 40	6 20 W.
	N. 5 W.	71 30	69 50	1 40 W.
	North.	68 50	70 20	1 30 E.
	N. 9 E.	63 40	71 40	8 0 E.
	19	60 10	74 10	14 0 E.
	position of Shore Compass shifted.			
	°			
October 13th	N. 24 E.	N. 64 0 W.	S. 46 0 E.	18 0 E.
	- 30 -	66 10	45 50	20 20 E.
	- 40 -	69 10	45 50	23 20 E.
	- 45 -	70 0	46 10	23 50 E.
	N.E. by E.	71 30	46 50	24 40 E.
	E.N.E.	71 30	47 40	23 50 E.
	E. by N.	70 50	48 50	22 0 E.
	East.	69 0	50 20	18 40 E.
	E. by S.	67 0	51 20	15 40 E.
	E.S.E.	65 30	52 50	12 40 E.
	S.E.	61 0	55 0	6 0 E.
	S.S.E. ½ E.	56 40	57 20	0 40 W.
	S. by E.	55 0	58 40	3 40 W.
	S. ½ W.	54 30	59 30	5 10 W.
	S.S.W.	52 0	59 50	7 50 W.
	S.W. ½ S.	50 0	59 50	9 50 W.
	S.W. by W.	46 30	59 50	13 20 W.
	W.S.W.	45 0	59 40	14 40 W.
	W. by S.	43 0	59 30	16 30 W.
	West.	41 0	59 0	18 0 W.
	N. 81 W.	39 10	58 30	19 20 W.

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* The curve is accordingly shown on the opposite page.

Having now the curve of deviations laid down from a large number of observations taken in various directions of the ship's head other than on the exact points:—Form a table of deviations for the thirty-two points of the compass, by measuring from the curve to the vertical line the corresponding values.

H.M.S. Achilles. Sheerness, October, 1864.

Deviation Table. Standard Compass.

Ship's Head by Standard Compass.	Deviation.	Ship's Head by Standard Compass.	Deviation.
	° ′		° ′
North.	1 40 E.	South.	4 30 W.
N. by E.	9 20 E.	S. by W.	6 0 W.
N.N.E.	16 40 E.	S.S.W.	7 30 W.
N.E. by N.	22 0 E.	S.W. by S.	9 0 W.
N.E.	24 10 E.	S.W.	10 30 W.
N.E. by E.	24 30 E.	S.W. by W.	12 20 W.
E.N.E.	24 0 E.	W.S.W.	14 20 W.
E. by N.	22 0 E.	W. by S.	16 0 W.
East.	19 0 E.	West.	18 0 W.
E. by S.	15 50 E.	W. by N.	19 50 W.
E.S.E.	12 50 E.	W.N.W.	20 50 W.
S.E. by E.	9 0 E.	N.W. by W.	21 0 W.
S.E.	6 0 E.	N.W.	19 30 W.
S.E. by S.	2 0 E.	N.W. by N.	16 30 W.
S.S.E.	1 0 W.	N.N.W.	12 0 W.
S. by E.	3 20 W.	N. by W.	5 30 W.

Formation of Steering Table.

You have rightly pointed out the difficulty of shaping an exact Standard compass course in a ship with large deviations when the correct magnetic course is given. It is obvious there should be no possibility of error in this important and constant operation: prepare, therefore, by the aid of Napier's diagram and the curve of deviations, a steering table for the Standard compass of H.M.S. Achilles, for every-day use.

H.M.S. Achilles. English Channel, 1864.

Magnetic Course proposed to be made.	Course therefore to be steered by Standard Compass in order to make the proposed correct Magnetic Course.
North.	N. 1° 0′ W., or nearly North.
N. by E.	N. 5 40 E. „ N. ½ E.
N.N.E.	12 0 „ N. by E.
N.E. by N.	19 0 „ N. by E. ¾ E.
N.E.	26 0 „ N.N.E. ⅜ E.
N.E. by E.	34 0 „ N.E. by N.
E.N.E.	43 30 „ N.E. ⅛ N.
E. by N.	54 30 „ N.E. ⅞ E.
East.	N. 66 0 E. „ N.E. by E. ⅞ E.
E. by S.	80 30 „ E. ⅞ N.
E.S.E.	S. 85 0 E. „ E. ⅜ S.
S.E. by E.	69 30 „ E. by S. ¾ S.
S.E.	54 0 „ S.E. ⅞ E.
S.E. by S.	37 0 „ S.E. ¾ S.
S.S.E.	21 0 „ S by E. ⅞ E.
S. by E.	7 20 „ S. ⅝ E.
South.	S. 5 0 W. „ S. ½ W.
S. by W.	18 0 „ S. by W. ⅝ W.
S.S.W.	31 0 „ S.S.W. ¾ W.
S.W. by S.	44 0 „ S.W. ⅛ S.
S.W.	57 30 „ S.W. by W. ⅛ W.
S.W. by W.	70 40 „ W. by S. ¾ S.
W.S.W.	84 30 „ W. ½ S.
W. by S.	N. 82 0 W. „ W. ¾ N.
West.	N. 69 30 W. „ W. by N. ¾ N.
W. by N.	58 0 „ N.W. by W. ⅛ W.
W.N.W.	48 0 „ N.W. ¼ W.
N.W. by W.	38 30 „ N.W. ½ N.
N.W.	29 40 „ N.N.W. ⅝ W.
N.W. by N.	22 30 „ N.N.W.
N.N.W.	15 0 „ N. by W. ⅜ W.
N. by W.	8 0 „ N. ¾ W.

SECTION IV.

Magnets, their action on each other and on soft iron—Earth's magnetism, and its effect on iron bodies—Action of magnets, and soft iron, when revolving round a compass, illustrative of the action of an iron ship.

The information given with reference to the compasses, to the formation of a table of deviations, to the construction of a curve of deviations and their uses, conveys sufficient information for the ordinary purposes of navigation; these several subjects are, however, independent of any theory: Is it not desirable that the educated seaman should have some knowledge of the laws according to which the forces causing the deviation act, and of the principles on which the deviations produced result from these laws?

A. It is desirable; for a knowledge of these laws and principles enables him to express the magnetical character of the ship by certain numbers or co-efficients, and by the aid of these to infer changes which the deviations will undergo on a change of geographical position. He will see that the observed deviations, however irregular they may appear, follow simple laws, and thus he will acquire confidence in his observations. He will be able to construct an approximate table of deviations by observations of deviation made on two or three points, and even by observations of a more special, though simple kind, made on a single point, before or arter the ship is launched.

These are unquestionably great advantages. How do you propose to explain the principles from which they are derived?

A. This may be done by considering in succession—

1st. The character of magnets; their action on each other, and on ordinary or soft iron.

2nd. The analogy existing between the magnetic character of the earth and a magnet.

3rd. The effect of the earth's magnetism in inducing magnetism in all iron bodies, and especially in iron-built ships.

4th. The action of magnets and soft iron, separately and together, on the compass-needle when revolving round it, as illustrative of the action of an iron ship on the compasses within board in producing the deviation.

Magnets, their action on each other and on soft iron.

Describe the characteristic features of a magnet.

A. A magnet is a steel or hard iron bar rendered magnetic by artificial means,* and by this process so excited, that at its opposite ends two opposite and equal forces are produced—one end receiving that kind of magnetism which is called north, the other end receiving south magnetism.

This magnet bar, when suspended so as to move freely in a horizontal plane, takes up a definite position—one end, commonly known as the north, or marked end, pointing towards the magnetic north, the other towards the magnetic south. The force which causes a magnet bar to take this definite position is not an attractive, but a directive force: because, while it attracts one end of the bar, it equally repels the other, so that on the whole the suspended magnet is not drawn either to the north or to the south.

The points of the magnet bar in which the attractive and repulsive forces may be considered as concentrated are known as the "poles," and are situated just within the ends.† The opposite properties of the ends of the magnet bar are manifested by the N., or marked end of one bar, repelling the N., or marked end of another bar, but attracting the S., or unmarked end, and *vice versâ.* Briefly stated, *like* polarities *repel; unlike* polarities attract each other.

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* There are various artificial means of magnetizing steel bars. A common process is to apply to the centre of the steel bar when laid on a table, the opposite poles of two magnets held obliquely at an angle of about 30°, and then to draw the magnets slowly along to either end of the bar. After this has been repeated a few times the steel bar is permanently magnetised.

A second process of magnetization is by placing the steel bar within the conducting wire of a voltaic battery which has been formed on a cylinder into a long hollow coil or spiral, and the electrical current sent through it. Very powerful magnets of large dimensions can be obtained by this method.

Steel or iron bars can be also magnetized by percussion. After repeated strokes by a hammer, when held in a vertical position, or better when held in the line of the dip, a considerable amount of magnetism is imparted.

Magnetism may be also communicated to steel or iron bars by contact with the natural magnet or lodestone, a mineral substance found in many parts of the world, especially in iron mines. It must, however, be remembered that whatever process is employed, there exists in every bar a limit of magnetic power which cannot be exceeded; at this stage the bar is said to be magnetised to saturation.

† The position of the pole in magnets of ordinary dimensions, may be assumed at about $\frac{1}{12}$th the whole length of the bar from their ends. The thinner the bars or needles, the more do the poles approach the extremities of the magnets.

The magnetic force of magnet bars is found to be chiefly confined to the surface; or, rather, their effect is the same as if the magnetic force were so confined. Small magnets are proportionally more powerful than large ones. The power of magnets is diminished by rise of temperature, temporarily or permanently according to the degree of heat applied.

The two polarities cannot be separated; a N. pole cannot exist in a magnet bar without a S. pole: hence, if the bar be broken into two or more pieces, each piece, and even the most minute fragment, will be found immediately to possess N. and S. poles.

[As the magnetism of the North end of a needle is of the opposite kind to that of the North pole of the earth, physicists are not agreed as to which should be called *north* magnetism; and it has therefore been found convenient to distinguish them by colour, calling the first red, the second blue. The distinction may be easily remembered by supposing the needle coloured, and from R occurring in noRth and in Red, U in soUth, and in blUe.]

What is meant by soft iron?

A. Soft iron is iron which is instantly magnetised by the approach of a magnetic body, but has no power of retaining magnetism.

What effect have magnets on soft iron?

A. The action of magnets on "soft" iron, differs materially from the action of magnets on each other, as will be seen by the following results: If we lay two magnets in a line at a short distance apart, with unlike poles turned to each other, and place a thin bar of soft iron between them, the latter becomes a temporary magnet while so situated: for the end next the N. pole of the one magnet will become a S. pole, and the end next the S. pole of the other magnet will become a N. pole; the iron bar has now become a magnet, or, as it is termed, received its magnetism by "induction."

But the effect is only temporary; for if we turn the iron bar gradually about its centre, it will as gradually lose the magnetism acquired by "induction;" when it is at right angles to the two magnets it will be in a neutral condition; and if turned further, its ends become magnetised in the opposite way.

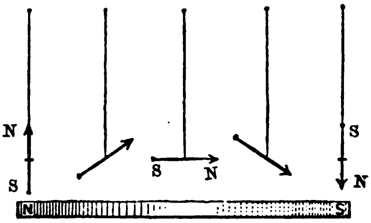
If a soft iron bar be presented end-ways to either pole of a suspended magnet, it will attract, though slightly, that pole; and it is indifferent which end of the iron bar is presented. In either case the pole of the magnet "induces" a pole of an opposite character in the iron bar; and between poles of opposite character as before stated, there is always attraction.

Magnetic character of the Earth and a magnet, their analogy.

Is there any analogy existing between the magnetic character of the earth, and that of an artificial magnet?

A. Yes; a striking analogy; for magnet bars suspended at the earth's surface are acted on much in the same way as one magnet is acted on when suspended over another magnet. If we take a magnet bar, and suspend by their centres over its entire length a number of small magnetic needles free to move in every direction, the following will be the results: At the N. pole of the bar, the S. end of the suspended needle will be attracted towards that pole; at the S. pole of the bar, the N. end of the suspended needle will likewise be attracted towards that pole; the suspended needle near the centre of the bar will take up a position parallel to the bar with its S. pole pointing to the N. end of the bar, and *vice versâ;* the needles suspended between either pole and the centre of the bar will incline or dip at various angles from the vertical, dependent on their relative distances between the poles and centre of the magnet bar. In this answer it is supposed that the earth's force may be neglected compared to that of the bar.

Fig. 1.



We have in this experiment a series of results analogous to the direction and angular amount of the dip of the needle to be found extending from pole to pole [magnetic] on the earth's surface.

Keeping this illustration in view, where on the earth's surface are those points over which a freely suspended needle would take a vertical position, in one case with its N. end downwards, in the other with its S. end downwards: and where would it assume a horizontal position?

A. Actual observations made by English navigators enable us to give, with a near approximation to the truth, the exact position of these two points. In latitude 70° N., longitude 96¾° W., the N. [*red*] end of a freely suspended magnetic needle points vertically downwards (*i. e.*, the dip is 90°), consequently this is the geographical position of the earth's north magnetic pole. [The earth here has consequently *blue* magnetism, and in reality represents the S. pole of a magnet.] In latitude 73½° S., longitude 147½° E., the S. [*blue*] end of a freely suspended needle points vertically downwards—this therefore is the geographical position of the earth's south magnetic pole. [Similarly the earth here has *red* magnetism, and represents the N. pole of a magnet.]*

*** See figures of Terrestrial Globe, Plate IV., at end.**

The line of successive places round the globe where the same freely suspended needle takes up a horizontal position with its N. end always pointing nearly to the earth's north magnetic pole, is the magnetic equator, and lies near the geographical equator. This "magnetic" equator is, in the Atlantic and eastern half of the Pacific Ocean, to the south of the geographical equator: in the Indian and western half of the Pacific Ocean to the north.*

These, then, are the actual poles, and the dividing line of the opposite polarities of the great magnet, the earth; but the distinctive feature must be remembered, that, preserving the now universal system of marking magnet bars and needles, the northern portion (geographically) of the earth's surface has south polarity, [or is a *blue* pole,] and the southern portion (geographically) has north polarity [or is a *red* pole].

What is the present state of our knowledge of the earth's magnetism?

A. Our knowledge of the distribution of magnetism over the earth's surface has greatly extended within the last half century; wide spread observations undertaken by governments as well as individuals, and investigations made by eminent geometricians, have placed before us exact results; and the values of the magnetic elements, *i. e.*, the variation of the compass (or magnetic declination), the dip (or inclination of the needle), and the earth's intensity of force, at any one geographical point may be now assumed as known within small limits. The general subject of terrestrial magnetism, nevertheless, still presents some of the most obscure and possibly the grandest features in natural science; but enough is, known for the requirements of the navigator, as he is concerned alone with the elements that affect the working of his compass, and the iron employed in the construction of his ship.

Explain the particular action of the earth's magnetism, on a suspended magnet.

A. When a magnetic bar or needle is freely suspended by its centre of gravity, and apart from the disturbing influences of other magnets or iron, it takes up a position both with reference to the geographical north, or true pole of the earth, and to the surface of the ground or horizontal plane.

The direction of the earth's magnetic force thus acting on the needle, sometimes expressed as the "line of force," is not (except on what may roughly be called two magnetic meridians, the one passing at present through the United States and Brazil, the other running along the Western coast of India, and passing through Australia) towards the geographical or "true" north, but to the east or west of it by an angle familiarly known as the variation of the compass: the "line of force" is only horizontal in the equatorial regions (as before described), and lies below or above the horizontal plane, when to the north or south of the magnetic equatorial line, by an angle equally familiarly known as the "dip of the needle:" for example, the direction of the line of force in London at the present time may be conceived as if the S. [*blue*] pole of a large magnet were directed 20° to the west of the true north and 68° below the horizon, and its N. [*red*] pole 20° to the east of the true south, and 68° above the horizon.

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* See figures of Terrestrial Globe, Plate IV., and Chart I., at end.

What relation exists between the earth's magnetic force or intensity and the variation and dip of the needle, and how is the earth's force distributed?

A. In answering this question, we must distinguish between the horizontal force, or that which acts to the magnetic north and directs the compass, and the total force, or that which acts in the line of the dip and directsthe dipping needle.

At the magnetic equator (along which the dip is zero) these two forces are the same. As we go to the north or south of this line, the horizontal force decreases till we come to a magnetic pole, of which, as has been just stated, there is one in each hemisphere, and where the dip is 90° and the horizontal force zero.

The total force, on the other hand, increases as we depart from the magnetic equator till we come to a point of maximum force or "focus," of which there are at present two of unequal force in each hemisphere, the focus of greatest intensity lying not very remote from the magnetic pole.*

What are the different modes of representing the amount and direction of the earth's force on the needle?

A. For this we must have three quantities given: it is most convenient for some purposes to consider the "horizontal" force, the "vertical" force, and the "variation." For other purposes it is more convenient to consider the "total" force, the "dip," and the "variation." For the study of the deviations of the compass it is most convenient to use a third system combined of the other two, and to consider the "horizontal" force, the "dip," and the "variation."

Can the other quantities, *viz.*, the total force and the vertical force be easily deduced from the latter quantities?

A. Yes, readily. The vertical force, which may be considered as that part of the total force acting vertically downwards is equal to the product of the number representing the horizontal force multiplied by the natural tangent of the dip. The total force is equal to the product of the number representing the horizontal force multiplied by the natural secant of the dip, or, which is the same thing, divided by the natural cosine of the dip.*

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* See figures of Terrestrial Globe, Plate IV., at end.

The meaning of the numbers attached to the lines in charts of the variation and dip is easily understood, as they simply indicate angular deviation from a definite direction; but what is the meaning of the number affixed to the lines in the chart of horizontal force?

A. All that is material as regards the horizontal force for the purposes of navigation is the proportion of the horizontal force in one geographical position to that at another geographical position; and, therefore, it is immaterial what number we have to represent the force at what may be called the base station. In the chart appended at the end of this work, the horizontal force at London, and the south coast of England generally, is taken as unity:† the figures affixed to other lines represent the proportion of the forces in them to the force at London.‡

Effect of Earth's magnetism in inducing magnetism in all iron bodies.

We have seen that by the action of a magnet bar, magnetism is induced in a soft iron bar, brought within its influence: what is the effect of the earth's magnetism on masses of iron at its surface?

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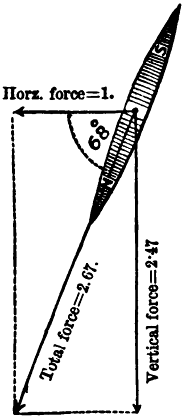
[*] The accompanying figure illustrates the relations between the several forces. In London, the needle dips 68° below the horizon; then, if we assume the horizontal component of the whole force pulling in that direction as unity, the vertical component of the same whole force acting on the needle is 2·47, and the whole or "total" force causing the dip is 2·67: for, the

Horizontal force × natural secant of dip = Total force.
" × " tangent " = Vertical force.
Total force × " cosine " = Horizontal force.
" × " sine " = Vertical force.
Vertical force × " cosecant " = Total force.

Fig. 2.



[†] To convert the values of the horizontal force on this scale, to the scale of absolute measure adopted by English magneticians, they must be multiplied by 3·85; to the scale adopted by the Continental magneticians, they must be multiplied by 1·77. See article "Terrestrial Magnetism," at end of this work.

[‡] For more accurate purposes, and in particular for comparing terrestrial magnetic force at different times, some measure must be obtained independent of the locality, and of the force of the magnet with which we observe: this is done by finding the force of the earth to turn a magnet of given size, shape, and strength, the measure of force depending on the units of weight and length adopted. See also article "Terrestrial Magnetism."

A. The magnetism of the earth similarly induces magnetism in every mass of soft iron on its surface: for example, if in England a rod of soft iron is held in the direction of the "line of force," its upper, or south end, becomes a S. [*blue*] pole, and attracts the N. [*red*] end of a compass needle; its lower, or north end, becomes a N. [*red*] pole, and repels the N. [*red*] end of a compass needle.

It follows from this that if a bar of soft iron be placed in a vertical position, its upper end will in north magnetic latitudes attract the N. end of the compass needle with a force proportional to the earth's vertical force:—*i. e.*, in London, with a force two-and-a-half times stronger than if the same bar were placed horizontally in the magnetic meridian. At the magnetic equator, the "line of force" is horizontal, and there a vertical bar of soft iron will not be magnetic. In south magnetic latitudes the "line of force" is inclined *upwards*, and there the upper end of a vertical bar of soft iron will repel the N. end of the compass needle.

What effect will be produced by the earth's magnetism in a horizontal bar of soft iron?

A. If the bar be placed in an east or west direction it will produce no effect on the compass needle, it being then at right angles to the line of force. If the bar be in any other position, its south end will attract, and its north end will repel the N. end of the compass-needle with a force proportional to the earth's horizontal force multiplied by the cosine of the azimuth of the bar measured from the magnetic north; for example: a bar placed horizontally in a N.W. direction, with its north end near the centre of a compass-needle, will repel the N. end of the latter (or attract the S. end) with a force only equal to $\frac{7}{10}$ths of what it would had the bar been placed in a meridional direction.

Thus far we have been speaking of soft iron, by which is understood iron that becomes instantaneously magnetised by induction when exposed to any magnetic force; but which has no power of retaining magnetism, all the magnetism that is received being transient. But in the constituent parts of a ship's hull or fittings, part of the iron may be hard, or iron of various degrees of quality between hard and soft may exist. What is the difference magnetically considered between hard and soft iron?

A. Hard iron thus differs from soft iron: it is less susceptible of being magnetised by induction either from the earth, or by artificial means; but when once magnetised it retains permanently a large part of the magnetism so received. It may be further considered that the greater the hardness of the iron, the greater is the amount of magnetism it is capable of retaining. Steel magnet bars are commonly known as, (and are indeed actually so, when properly manufactured), permanent magnets.

If, however, a bar or plate of soft iron be retained in a position favourable to induction from the earth's, or other magnetic force, and is then exposed to mechanical violence by being hammered, or twisted, or bent, the amount of magnetism it receives is increased, and it becomes for a time a true magnet. The magnetism so received diminishes, however, sensibly by time; rapidly in the first few days or weeks, but a portion remains for months, and may for years. This condition is known as *sub-permanent* magnetism. It must be observed that if renewed mechanical violence be applied in a different or opposite position of the bar, the magnetism originally developed will be diminished, or disappear.

What is the effect of the earth's action on a spherical mass of soft iron—as a cannon ball, or thick iron shell?

A. A spherical mass, whatever its position, assuming it to be soft iron,* becomes a magnet whose poles point in the direction of the line of dip or force at the place [in north magnetic latitudes, N. [*red*] pole downwards]. The great circle at right angles to this polar axis (which may be called the equator), is entirely neutral, and here the effect of the sphere's magnetism is almost exactly equal and opposite to that of the earth, so that a small compass needle carried round this line will be found unaffected by the earth and ball: the same needle brought near the poles will be strongly attracted or repelled.

Experiments have been made to measure the time taken for the induction of magnetism in shot and shells rolled in the meridian; it was found that they could not be rotated fast enough to alter the N. [*red*] pole from its position near the bottom or under part of the sphere.†

Are similar effects produced on bodies of irregular shape; such, for example, as the guns and several fittings in a ship, and indeed on the general body of the ship?

A. Yes, but the mutual action of the magnetic portions complicates the problem, and prevents us from drawing any but very general conclusions.

In a wood-built sailing ship, there are necessarily numerous iron bolts and masses. In wood ships of modern construction, iron beams and uprights are extensively adopted: in wood steam-vessels, the engines in their separate parts, boilers and funnels materially increase the amount of iron on board. All these fittings and appliances, including guns, &c., may be considered as individual masses, with their *upper* parts (in north magnetic latitudes) developed into S. [*blue*] poles of so many temporary, or sub-permanent magnets, their *lower* parts into N. [*red*] poles, and with a neutral plane running across or round each mass. This result necessarily follows, that if a compass be placed in the after part of any wood-built ship, and above the upper deck, the N. end of the needle will be drawn to the head of the ship in north magnetic latitudes, and, unless the iron has a large amount of permanent magnetism, to the stern in south magnetic latitudes.

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* Cast iron does not appear usually to possess permanent magnetism. Astronomer-Royal, "Philosophical Transactions, Royal Society," 1839, p. 190.

† Report of the National Academy of Sciences, United States, for 1863—Compass Committee, pp. 78-79.

As the law of induction applies to bodies of the most complex form, it may be anticipated that the magnetism of the hull of an iron ship so received, must become highly developed, and to a certain extent fixed by the hammering it undergoes in the progress of construction. Is this so; and how is the magnetism distributed?

A. Early experiments on iron ships brought prominently to view this interesting fact, *viz.*, that the hull acts as a permanent magnet on compasses placed outside the vessel as well as on those placed inside: an iron ship must therefore be viewed in its effect on a properly placed magnet rather as one great magnet, than as an aggregation of smaller magnets.

Keeping in view that the inductive effect from the earth's magnetism is greatest in the line of the dip, and the existence of a neutral equatorial plane at right angles to the line of dip in spherical bodies; we are prepared to see that each iron ship must have a distinct distribution of magnetism depending on the place of building, and the direction of the head and keel while building; the ship's polar axis and equatorial plane conforming more or less to the line of dip of the earth at the place where built, and a plane at right angles to that line: abundant observation and experiment have proved this important general principle.

To illustrate this principle: let us suppose, as in the following figure 3, that four iron ships* are building on the cardinal points of the compass, in a port in England where the dip of the needle is 70°.

In Fig. of ship built head north: the after body of the ship would have S. [*blue*] polarity, and the fore body N. [*red*] polarity; the upper part of the stern would have the S. [*blue*] polarity developed in a high degree; the lower part of the bow would have the N. [*red*] polarity equally developed. At the stern the N. end of a compass-needle would be strongly attracted; at the bow the S. end of the needle would be strongly attracted.

In Fig. built head east: the whole of the upper part of the ship would have S. [*blue*] polarity; the whole of the lower part would have

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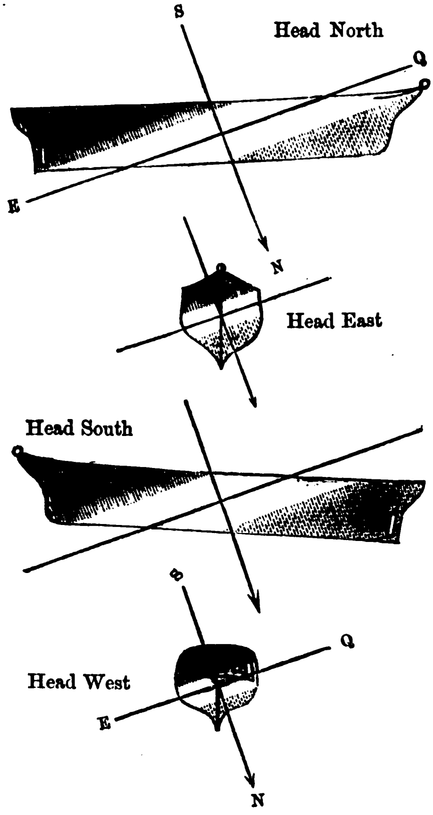
* Or four composite built ships, with ribs, beams, stanchions and deck-girders of iron.

N. [*red*] polarity; but the magnetism of the starboard side of the upper works would be developed in a higher degree than the port side, and the N. end of a compass needle, if carried along the upper deck from end to end, would be attracted to the starboard side.

Fig. 3.



In Fig. built head south: the magnetic conditions of Fig. head north are reversed; now the fore body of the ship has S. [*blue*] polarity, and the after body N. [*red*] polarity: the upper part of the bows has S. [*blue*] polarity developed in a high degree, and the lower part of the stern N. [*red*] polarity equally developed. At the stern the N. end of a needle would be repelled, and also attracted to the strong S. [*blue*] pole at the bow.

In Fig. built head west: the magnetic conditions of Fig. head east are reversed; the whole of the upper part of the ship has still S. [*blue*] polarity, and the lower part N. [*red*] polarity; but the magnetism of the port side of the upper works is developed in a higher degree than the starboard side; and the N. end of a compass-needle, if carried along the upper deck from end to end will be attracted to the port side.

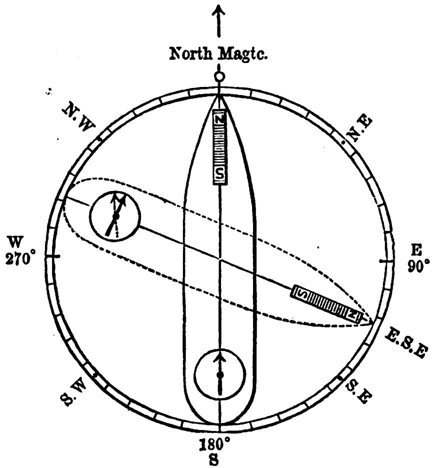
Action of magnets and soft iron, when revolving round a compass, illustrative of the action of an iron ship.

The hull of an iron ship being a large magnet, the movement in azimuth of this large magnet necessarily produces a varying disturbance of the compass; how would you illustrate this disturbance by experiment?

A. Place a small compass—the smaller the better, if the motions of the needle be distinct—in the centre of a table. Take a bar (not a horse-shoe) magnet, which placed at a convenient distance east or west of the compass, and pointing towards it, will produce a deviation of say about two points, or 22½°. It will be found most convenient to direct the S. [*blue*] pole of the magnet to the compass so that the magnet may attract the N. end, and repel the S. end of the needle: make also arrangements so that the magnet may be moved round the compass always at the same distance from it,* and with the same pole directed towards it. Then we shall observe the following phenomena.

When the magnet is north of the needle there is no deviation, but if we disturb the needle and cause it to vibrate, it will vibrate more quickly than if the magnet were removed.† As the magnet moves on to the east, the needle will deviate to the east by a greater and greater amount,

Fig. 4.



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* This may be done by drawing a series of circles about the position of the centre of the compass, and graduating their circumferences into single or five-degree or half-point spaces as convenient; marking as zero the north extreme of the line passing through the axis of the needle when at rest, *i. e.*, the line of the magnetic meridian. A small table fitted with arms—or the deck figure of a ship—made to revolve about a centre, graduated as in figure 4, will be found well adapted for this class of experiment.

† On account of the magnet adding its force to the directive force of the earth.

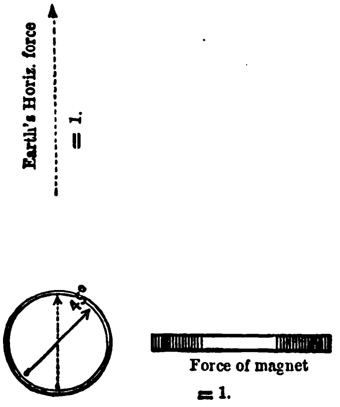
till, when the magnet is about E.S.E. from the compass, the needle will point about N.N.E., so that the directions of the needle and of the magnet are at right angles to each other, when the deviation will be a maximum. The deviation will then diminish, but of course more rapidly than it increased, till, when the magnet is south of the needle, there will be no deviation,—but if the needle is disturbed it will vibrate more slowly and sluggishly than if the magnet were removed.* In the western semicircle the deviation will be the same in amount, but opposite in direction, and, as will be hereafter seen, the deviation in each case is proportional to the sine of the azimuth of the direction of the magnet measured from the direction of the disturbed needle.

What is here described represents exactly the part of a ship's deviation which is called the "semicircular," for, in the complete revolution of the magnet, the N. end of the needle deviates to the east for one half the revolution, and to the west for the other half; and hence the name.

What is the relation between the amount of the deviation of the needle and the force of the magnet producing it?

A. When the needle is free in its action, we may assume the value of the invisible force—always urging or retaining it in a meridional direction—that is, the earth's horizontal force, as unity, or 1. If a magnet be placed on the table, at right angles to the needle when at rest or on the east and west lines of the table, and at such a distance from the needle that the deviation shall be exactly 45°, it is obvious that the force of the magnet in that position equals the force of the earth, as the needle is retained midway by their joint action. (See fig. 5.)

Fig. 5.



It will be readily understood from this illustration, that if a magnet, whatever its dimensions and force, be placed so near a compass-needle as to exert a force greater than that of the earth, the needle, in the entire revolution of the magnet round it, no longer obeys the earth's force, but for a part of the revolution follows the magnet: if the magnet, however, is placed at such a distance from the needle that its force is less than the earth's, its effect resembles the action of an iron ship on a properly placed compass; the compass-needle is everywhere subject to the earth's dominant force, but with an amount of deviation depending on the relative values of the forces of the magnet and the earth.

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* On account of the force of the magnet acting in antagonism to the earth's directive force.

How is this relative force of the magnet conveniently measured?

A. Either by observing the deviation produced when the magnet is east or west of the compass-needle when undisturbed (or 90° from zero of table), or by observing the greatest deviation of the needle that can be produced by the magnet. The *natural* tangent of the first deviation, or the *natural* sine of the maximum deviation alike give the force of the magnet in terms of the earth's horizontal force considered as 1.

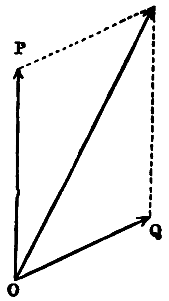
Can a semicircular deviation be produced by the action of a soft iron bar?

A. A semicircular* deviation is so produced if the bar is in a vertical, or indeed in any but a horizontal position, for we have seen that a bar of iron in such a position becomes a magnet by induction from the earth's vertical force; the upper end—in England—being a S. [*blue*] pole, the lower end a N. [*red*] pole: but there is this difference as to the effect produced—*In the case of the magnet*, the force being constant, the deviation produced on a given azimuth is inversely proportional to the antagonistic force which it has to overcome in producing deviation—that is, to the horizontal force of the earth; *in the case of vertical iron magnetised by induction*, the effect produced, being directly proportional to the earth's vertical force, as well as inversely proportional to the horizontal force, is therefore directly proportional to the tangent of the dip.

Having the force of the disturbing magnet given, show how, by simple geometrical considerations, we can find for any azimuth of the magnet, as it revolves round the needle—(1) the deviation it will produce, and (2) the directive force of the needle, both as resulting from the combined action of the magnet and the earth.

A. The first step must be an acquaintance with the simple theorem, which is the foundation of all theoretical mechanics—the "parallelogram of forces;" for example:—as in Fig. 6.

Fig. 6.



Let O P, O Q represent in magnitude and direction two forces acting on the point O. Complete the *parallelogram* O P Q R, and draw the diagonal O R; then the two forces O P and O Q combined are precisely equivalent to a single force O R.

We get the same result by drawing the one force from the extremity of the other, and completing the *triangle*. Thus, as in the following figure 7, we may draw P R at the extremity of O P, and joining O R, we get O R by drawing two lines instead of four.

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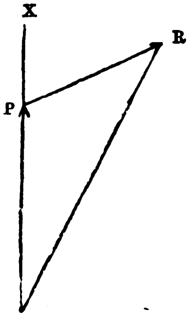
* **It may be convenient for the student to know that in some of the investigations of**

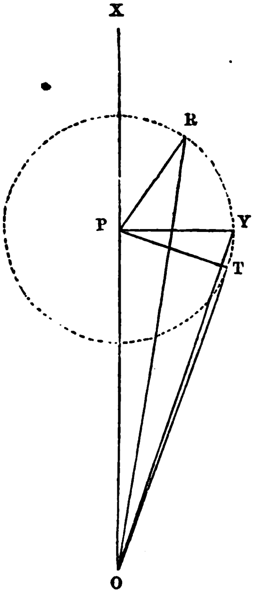
Fig. 7.



If, now, O P represents the directive force of the earth on the north end of the needle (= 1) to be taken from a scale of equal parts; P R the force of the magnet; then the direction O R will represent the direction assumed by the needle, and the length O R will represent the directive force on the needle;* P O R is the deviation; X P R the magnetic azimuth of the magnet.

If we now wish to find the deviation produced by the magnet on different azimuths we can easily do so. See Fig. 8.

Fig. 8.



By drawing a circle with centre P, and radius P R, we have only to take X P R = the azimuth of the disturbing force, to get P O R, the deviation.

We also see that the deviation goes on increasing till we come to the point T, at which O T is a tangent to the circle; and at which point P O T † is the angle of which the sine is P T to radius O P.

Or, if H be the horizontal force of the earth, M that of the magnet; the sine of the maximum deviation $= \frac{M}{H}$; and we also see that when the magnet is at Y, *i.e.*, when it is east or west of

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the Astronomer-Royal on the subject of the magnetism of iron ships, the term "polar-magnet" is applied to this deviation.

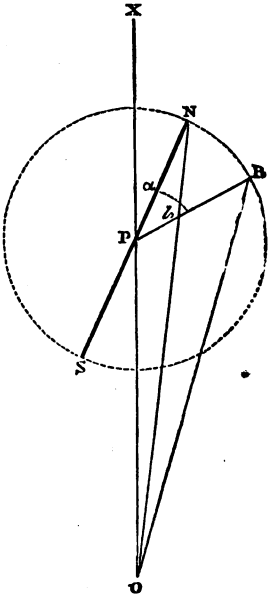
* Or, we may obtain the directive force on the needle by the following observation: note the time, in seconds, required for a given number [10, 20, 30, &c.] of vibrations when the magnet is *in* position, and when *removed*. The square of the second time divided by the square of the first time, gives the proportion of the directive force in the disturbed state, to the directive force in the undisturbed state; the resulting value also equals the length of the line O R. These vibrations are best observed when the needle is suspended by a fibre of silk; but if the needle be finely mounted in the usual way, accurate results can also be obtained. As will be seen in the sequel, this is one of the most important and valuable observations that can be made on board ship, in connection with her magnetic state, as well as for the purpose of obtaining a table of deviations when on the stocks or in dock. (See Sections VII. and VIII.)

† Which is obviously the maximum deviation.

the needle, $\frac{M}{H}$ = the tangent of the deviation, as stated in the preceding page.*

How must the figure be modified if the imaginary magnet is not in the fore and aft line?

Fig. 10.



A. The magnet, we have said, gives an exact representation of the force causing the semicircular deviation observed in ships, but we must remember that in a ship the imaginary magnet which might replace the iron of the ship may not be in the midship or fore and aft line; and therefore the azimuth of the magnet may not be the azimuth of the ship's head, but will differ from it by the angle between the direction of the ship's head and that of the magnet.†

Thus, as in Fig. 10, suppose the magnet to lie in a direction making an angle XPN $= \alpha$, to the right of the ship's head, α being what is called the "starboard angle;" then when the ship's head is north, the deviation will be PON, and to obtain the deviation when the ship's head is on any azimuth ζ, we must measure the angle ζ from PN; so that, if NPR $= \zeta$, POR will be the semicircular direction on that azimuth.

In every position the directive force is represented by the distance of the point R from O.

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* If we wish to express the deviations in terms of either the magnetic azimuth, or the compass azimuth of the magnet, (see Fig. 9,)

Let us call POR $= \delta$, the deviation,

MPR $= \zeta$, the magnetic azimuth,

PRO $= \zeta - \delta = \zeta'$, the compass azimuth:

Then MR $= M \sin \zeta$,

MP $= M \cos \zeta$,

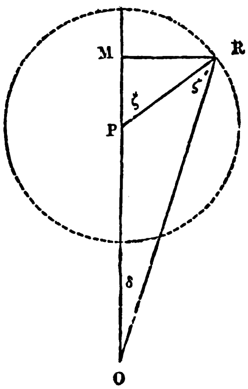
OM $= H + M \cos \zeta$,

$$\tan \delta = \frac{MR}{OM} = \frac{M \sin \zeta}{H + M \cos \zeta} = \frac{\frac{M}{H} \sin \zeta}{1 + \frac{M}{H} \cos \zeta},$$

$$\sin \delta = \frac{PR}{OP} \sin \zeta' = \frac{M}{H} \sin \zeta'.$$

Which expressions are exact, and give the deviations in terms of the magnetic and compass azimuths.

Fig. 9.



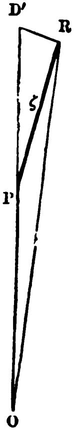
† It will be remembered that in all cases for simplicity,

In what manner does a horizontal rod of soft iron revolving round a compass differ in its action from a magnet bar?

A. If we substitute for the magnet a horizontal rod of soft iron directed towards the needle and lying before or abaft it, the phenomenon is wholly different, because, as we have seen, the magnetism of the rod is not constant, but varies as the cosine of the azimuth of the rod from the north.

So that, if O P, Fig. 11, represents the direction of the magnetic north, and P D′ the force of the rod when pointing north, then, when it is in any other direction P R, and if we take D′ R perpendicular to P R, P R will represent the force as well as the direction of the action of the magnetism of the rod. Hence the difference between the curves traced out by the point R, according as P R represents the force of a magnet or of a horizontal rod of soft iron is this:—in the first case, R will describe a circle of which P is the centre, P D′ the radius; in the second case, it will describe a circle of which P D′ is a diameter—and this on account of the property of the circle, that the angle in a semicircle is a right angle. When, therefore, the rod is north, there is no deviation; as the rod moves to the east it causes an easterly deviation, which is a maximum when it is a little past N.E. When it is east there is no deviation; when it is in the S.E. quadrant the deviation is westerly; when in the S.W. quadrant it is easterly; when in the N.W. quadrant it is again westerly. It thus changes in every quadrant, and produces a deviation of the kind called quadrantal.*

Fig. 11.



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the imaginary magnet is supposed to be in the same horizontal plane with, and directed to the compass, the S [*blue*] end of the magnet being directed to the compass.

* If instead of a soft iron rod entirely before or abaft the needle, we have a transverse soft iron rod with its centre immediately below or above the centre of the needle, it is not difficult, on careful consideration, to see that a precisely similar effect will be produced as regards the deviation, but that the circle though passing through P as before will lie towards O, and thus such a rod will produce a similar quadrantal deviation, but will diminish the directive force. If both rods act, the effect on the deviation and force will be represented by drawing a circle whose radius is the mean of the radii of the two circles, and whose centre is half way between the centres of the two circles. We shall thus have an increased quadrantal deviation, and the directive force will be increased or diminished according as the force represented by the fore and aft or the transverse rod predominates.

In the text, for simplicity, the effect of the fore and aft rod is alone considered. In many iron ships the fore and aft rod itself must be considered as having its centre immediately above or below the compass. In that case the directive force is much diminished without a large quadrantal deviation being produced.

SECTION V.

On the analysis of a table of deviations—The semicircular, quadrantal, and constant deviations—The co-efficients A, B, C, D, E, their physical meaning—Ship's permanent and induced magnetic forces.

The action of magnets and detached masses of soft iron on the needle having been now considered, explain the action of the forces on board ship producing the compass deviation.

A. The whole disturbance of the compass may in general be represented as the sum of the effects of two forces: one force produces a "semicircular" deviation, the neutral or zero point of which may be in any direction; the other force produces a "quadrantal" deviation. The whole deviation is the algebraic sum* nearly of these two deviations. The practical problem, therefore, presents itself of analyzing a table of deviations, so as to distinguish the two parts of which it consists, *viz.*, the semicircular deviation, and the quadrantal deviation.

In some special cases there is a "constant" deviation, which must be taken into account.

Semicircular, quadrantal, and constant deviations.

Describe in detail the nature, the law, and the modes of representing the semicircular deviation?

A. The "semicircular" deviation is so named from being easterly in one semicircle, and westerly in the other, as the ship's head moves round a complete circle in azimuth. The points of no deviation, or neutral points, are opposite to each other; and the deviation, or more exactly the sine of the deviation in each semicircle, is proportional to the sine of the azimuth of the ship's head measured from the neutral point, *the azimuth being that shown by the disturbed compass.*

This may be illustrated by the following figure 12, which represents the general curve of semicircular deviation in wood-built ships in north latitude. In this figure, as in Napier's diagram, we may consider the vertical line as the margin of a compass card cut at the north point, and straightened out. The neutral points are assumed, as they generally are in wood-built ships, at north and south; the maximum points are then at east and west by disturbed compass. Assuming the maximum deviation as 10°, then the deviation at the successive points in the first quadrant, N. by E., N.N.E., N.E. by N., N.E., N.E. by E., E.N.E., E. by N. by the disturbed compass, will be represented by lengths equal to 10° multiplied by ·195, ·383, ·556, ·707, ·831, ·924, ·981, which are the sines respectively of the above rhumbs, 11¼°, 22½°, 33¾°, 45°, 56¼°, 67½°, 78¾°; the result is 1° 57′, 3° 50′, 5° 33′, 7° 4′, 8° 19′, 9° 14′, 9° 48′—Easterly deviation being represented by + sign. In the second quadrant (from east to south) the deviations are in reverse order. In the third quadrant, the deviations are as in the first quadrant, but being Westerly are represented by a — sign. The fourth quadrant is the same as the second quadrant, with the signs reversed.

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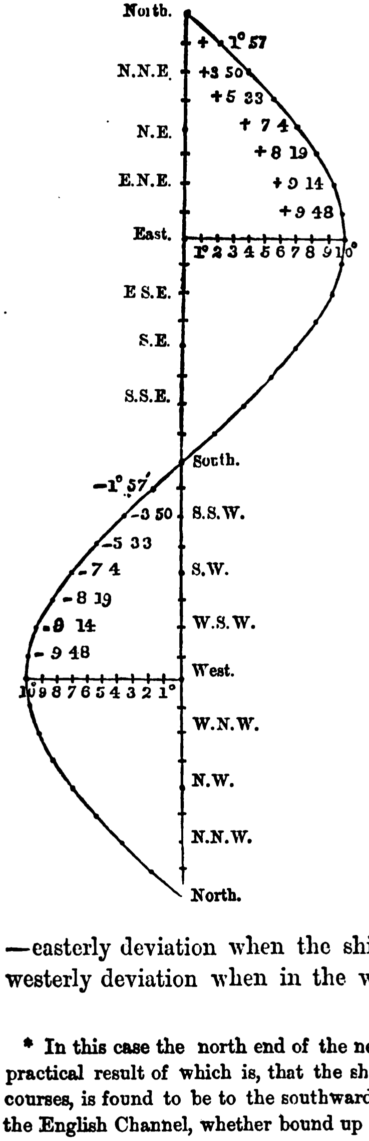
* See page 55, note †.

Fig. 12.



It is important here to note the distinctive difference that exists between the arrangements of the semicircular deviation of the wood and the iron-built ship; the general type of the former has been shown in figure 12, the neutral points being at or near the north and south points—easterly deviation when the ship's head is in the eastern quadrants, westerly deviation when in the western quadrants.* In the iron-built ship the neutral points *approximate to those points of the compass to which the ship's head and stern were directed in building.* It follows that the deviation is easterly when *the part of the ship which was south in building* is east of the compass, westerly when west.

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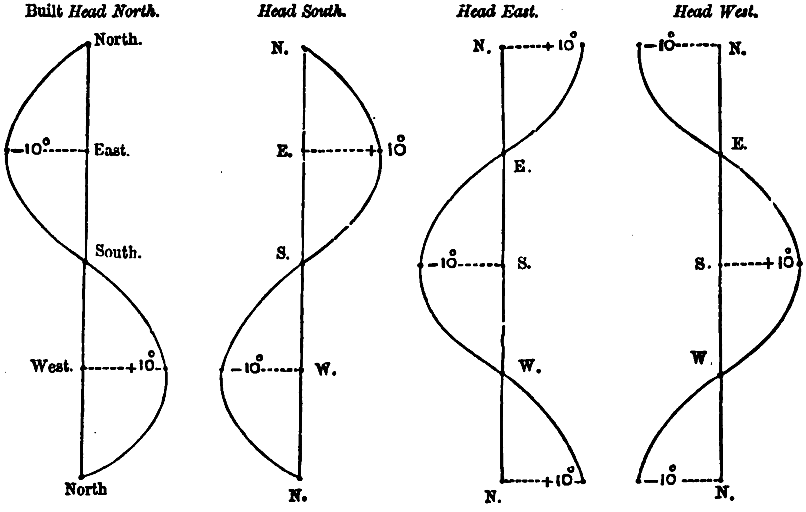
* In this case the north end of the needle is drawn towards the ship's head; the practical result of which is, that the ship's true place, when on easterly or westerly courses, is found to be to the southward of her place by dead reckoning. Hence, in the English Channel, whether bound up or down, wood-built ships are, as a rule (when the deviation is unallowed for), carried towards the French coast. An iron ship, built head north (see following paragraph in text), would, on the contrary, be carried in on the English coast.

[This may be stated in another way. If the ship is on the azimuth of building, the semicircular deviation will be small, and the directive force a minimum. If on a precisely opposite direction, the semicircular deviation will be likewise small, but the directive force a maximum.]

These results are illustrated by the following curves of semicircular deviations of four iron ships respectively built head north, south, east, west.

Fig. 13.

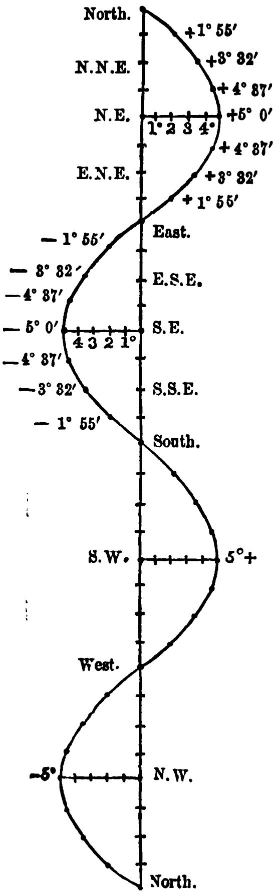


In the ship built head north, there is no deviation of the compass needle towards either side of the ship while she lies in a north or south direction, but with her head in all other directions there is a deviation towards the stern (see *ante*, p. 33); hence, when her head is in the eastern quadrants there is westerly deviation, in the western quadrants easterly deviation. In the ship built head south, the conditions are reversed, as the attraction is towards the bow.

In the ship built head east, there is no deviation to the bow or stern when her head is east or west, but with her head in all other directions there is a deviation to the starboard side immediately abreast of the position of the compass; and hence, with the head north, there will be found the maximum of easterly deviation, and with the head south the maximum of westerly deviation. In the ship built head west the conditions are reversed, as the attraction of the needle is to the port side of the ship (see *ante*, p. 34).

From these conditions it will be readily understood that, given the direction of the iron ship's head in building, the character of the curve of semicircular deviation can be approximately predicted.*

Fig. 14.



Describe similarly the quadrantal deviation.

A. The quadrantal deviation is so named from its being easterly and westerly alternately in the four quadrants, as the ship's head moves round a complete circle in azimuth; its zero points in general coincide very nearly with the cardinal points of the compass, and its amount is proportional to the sine of *twice* the compass azimuth of the ship's head (or more accurately, to the sine of twice the azimuth of the ship's head measured from a line halfway between the correct magnetic north, and the north of the disturbed needle).

This may be illustrated by the annexed figure 14, which represents the curve of quadrantal deviations of *all* iron ships† and most wood-built ships; the deviation is easterly in the N.E. and S.W. quadrants, westerly in the S.E. and N.W. quadrants, or follows the law of signs + — + —.

In this example the maximum amount of quadrantal deviation is assumed as + 5°, and the amount of the deviation for the intermediate points N. by E., N.N.E., N.E. by N., is found by multiplying 5° by the numbers ·383, ·707, ·924, the sines respectively of *twice* the above rhumbs, or 22½°, 45°, 67½°, the result being 1° 55′, 3° 32′, 4° 37′; the points N.E. by E., E.N.E., E. by N., are the same values in reverse order; and so on alternately with + and — signs in the successive quadrants.

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* In this prediction it is assumed that no local disturbing influences on the compass exist; such as undue proximity to the rudder-head, or a vertical mass, such as a funnel, capstan, spindle, &c.

† In a mast compass considerably elevated above an iron ship's hull, examples of the quadrantal deviation following the signs − + − + have been observed, but very small in amount; similarly also in wood screw-vessels with the compass over the screw shaft.

What is the constant deviation?

A. When the easterly deviations exceed the westerly, or *vice versâ*, then, in addition to the terms of the formula, which change with the position of the ship's head, we must include a constant term. This is called the constant deviation.

It is, however, very small, and generally an error of observation or instrumental error, not a true deviation.

What amount of semicircular and quadrantal deviation may we generally expect to find in various classes of ships while in England?

A. The semicircular deviation in wood-built ships of war seldom exceeds 10°. In iron-built ships,* both of war and commerce, even in the most carefully selected position, it frequently exceeds 20°, and even 30°.

The quadrantal deviation in wood-built ships seldom exceeds 1° or 2°; in ordinary iron-built ships it ranges from 3° and 4° to 6° and 7°; in some of the armour-plated ships of war it has been found to amount to 8½° at the Standard compass; and to 14° and 15° in compasses less favourably placed.

Then, with these varying values, we may nevertheless assume that, however irregular the deviations may appear in tables, or in a curve, such apparent irregularity arises simply from the mode of super-position of the parts of the two deviations, as in fact each part is perfectly regular?

A. Such is the case. The deviations of wood-built ships are generally regular in appearance from the small amount of quadrantal deviation, and from the semicircular and quadrantal deviation having the same zero points, so that the curves are symmetrical on each side the vertical line. In iron-built ships, from the different positions of their zero points, the curves of deviation are in general not symmetrical, and occasionally assume an appearance of irregularity, but they are nevertheless in perfect obedience to the laws above stated.

The following figures, 15, 16, (shown on the next page,) illustrate the curves of two iron ships built head north and head east (with a maximum semicircular deviation of 10°, and a maximum quadrantal deviation of 5°), as showing the superposition of the two parts. The resulting curve of deviations is given by the dark line.

Does the semicircular deviation undergo change, when the ship changes her place? and if so, according to what law?

A. In all ships the semicircular deviation changes with a change of geographical position. In *wood-built* ships it varies as the ratio of the

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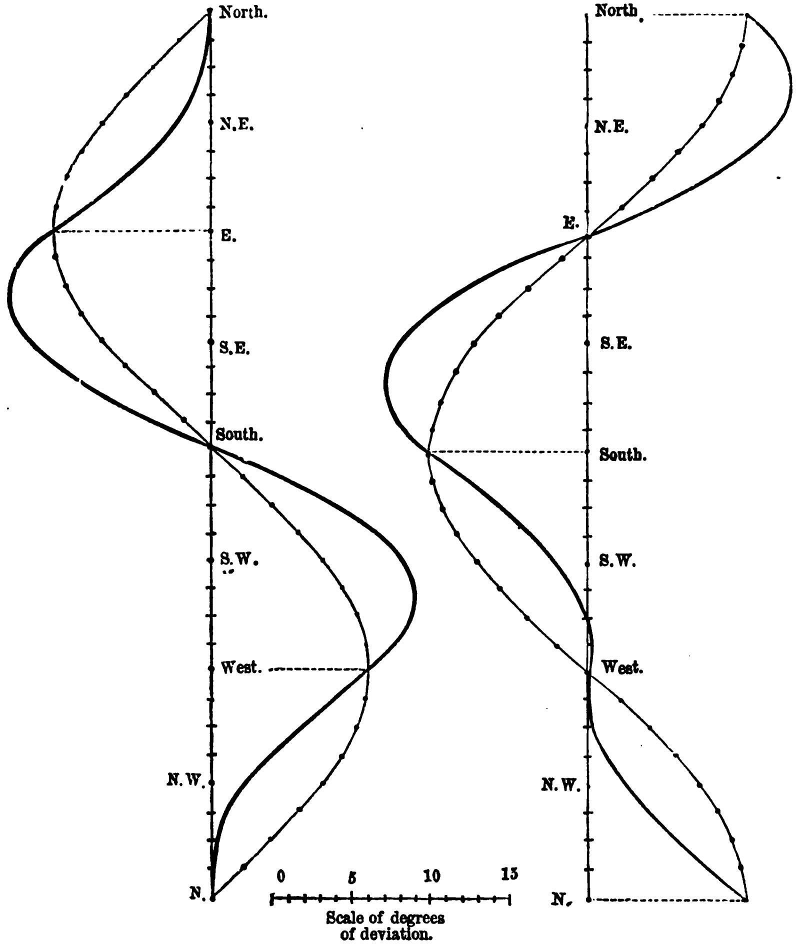
* As also in composite-built ships.

Fig. 15.

Built *head North.*

Fig. 16.

Built *head East.*



earth's vertical force to the horizontal force,*, or in other words, as the tangent of the magnetic dip at the place; therefore, when the ship is at the magnetic equator, and the earth's magnetism acts horizontally, the dip being 0, this deviation becomes zero,† and changes its sign (*i.e.*, easterly deviations becoming westerly, and westerly deviations easterly), when the ship passes from north to south magnetic latitudes. We see from this that the changes of the ship are analogous to the changes that the magnetism of a vertical soft iron bar would undergo; the effect being, that the north end of the needle, which in the northern hemisphere is drawn towards the bow of the ship, is in the southern hemisphere drawn towards the stern.

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* The earth's vertical force is here the *cause* of the deviation—the earth's horizontal force being the *directive force* of the compass needle; the deviation is, therefore, directly proportional to the vertical force, and inversely proportional to the horizontal force.

† As the induced magnetism in the iron of wood-built ships requires a little time for

In *iron-built* ships the changes are more complicated from their semicircular deviation, being mixed up or consisting of two parts. One of these, the induced part, resembles that of wood-built ships, and consequently varies as the tangent of the dip; this is in general the smaller part. The other and greater part is that which has its zero or neutral point when the ship's head or stern is on, or near the point on which the ship's head was directed when building; this part, which may be termed the permanent part, varies inversely as the earth's horizontal force at the place.* It will therefore diminish as we approach the line of greatest horizontal force, which does not differ much from the magnetic equator, and increase as we leave it on either side.

Then it may be inferred that if we knew the exact proportions of the two parts of the semicircular deviation, and if these proportions remained unchanged, we could predict the changes the deviations would undergo in different latitudes?

A. We could; but as ships are constructed of various kinds and qualities of iron, the magnetic character of which undergoes change, it is impossible—at least in new ships—to allot the exact proportions. We are certain, nevertheless, from experience, that in the majority of iron ships, their magnetism, after a year or two of sea service, assumes a nearly permanent condition, and then their changes on change of place can be predicted within a moderate approach to accuracy.

Does the quadrantal deviation undergo changes on the ship's change of place?

A. No. This deviation has the remarkable property of remaining unchanged in all magnetic latitudes, and of being little changed by lapse of time. Once, therefore, determined for a particular compass in a ship, its unchangingness may be relied on, so long as the distribution of the iron in the ship is not materially changed.

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its complete development, the semicircular deviation is thus generally in arrear, and is more nearly proportional to the tangent of the dip, at the place at which the ship was a few days previously.

* The effect of a disturbing cause of fixed amount—such as a permanent magnet—in producing deviation, is *inversely* as the directive force of the earth.

From what causes do this remarkable property arise ?

A. The property of horizontal soft iron producing the same amount of deviation in all parts of the world is thus explained. The magnetic force of the earth is the directing force acting on the needle: the induced magnetism of the horizontal soft iron is the disturbing force acting on the needle; the intensity of the latter force varies as that of the former, and therefore the ratio between the two forces being always the same, the effect produced is the same.

Co-efficients A, B, C, D, E, their physical meaning.
Ship's permanent and induced magnetic forces.

What advantages are derived from analysing a table of deviations ?

A. We are enabled to express the magnetic character of the ship by a few constants or co-efficients; which co-efficients not only give the whole effect of a table of deviations in a short form, but denote the causes of the several parts of the deviation: the various types of wood and iron ships can thus be classified, and general inferences drawn as to the changes of the deviation on a change of time, or place, which could not otherwise be drawn.

Explain the nature of these co-efficients.

A. Five co-efficients, distinguished by the letters A, B, C, D, E, represent the several parts of which the deviation of the compass is composed :* their physical meaning may be thus described:

A represents the "constant" deviation, to which a + sign is affixed, if easterly deviation is in excess, a — sign if westerly deviation is in excess. It is desirable to remember that this part of the deviation may be either real or apparent. For a compass placed in the middle line of the ship, the value ought to be very small (under 1°), and if, therefore, this amount is exceeded, some *apparent* error must be assumed: this apparent error may be due to the prism, or index error of the compass on board, or of the compass employed on shore in obtaining reciprocal bearings, or may arise from a local disturbance in the position of the latter; or when the deviations have been observed by the bearings of a distant object, its correct bearing may have been imperfectly determined, or, if when at sea, the deviations have been determined by azimuths of the sun, the variation of the compass allowed may have been in error.†

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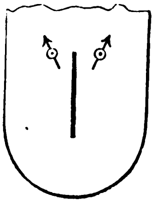
* When the deviations much exceed 20°, and great accuracy is required, these co-efficients are represented by the letters of the German alphabet 𝔄, 𝔅, ℭ, 𝔇, 𝔈. The Roman letters represent a certain number of degrees and minutes; the German letters represent the natural sines (nearly) of the arcs of the corresponding Roman letters.

† In the case of compasses which are compared with the Standard to obtain their deviations (see note, p. 20) an apparent A will be produced unless their lubber-lines are exactly fore and aft.

A *real* constant deviation will arise from the induction of the horizontal force of the earth on elongated masses of soft iron unsymmetrically distributed : a compass out of the middle line of the ship may therefore have a *real* A ; as for example, in two compasses, before the steering wheel, the spindle of which is iron, see accompanying figure 17, where the spindle end, near the compasses, constantly attracts the south end of the needles, as the ship swings round from east (by north) to west ; and their north ends as the ship swings from west (by south) to east ; + A being given to the starboard compass, – A to the port compass.

Fig. 17.



A *real* co-efficient A does not change on change of latitude : but an *apparent* A may have different values at different places, according to the circumstances above described.

B and C are the co-efficients of the "semicircular" deviation. B represents the fore and aft magnetic forces of the ship, and has its zero effect on the deviation when the ship's head is north or south, its maximum when the ship's head is east or west. C represents the transverse force of the ship, and has its zero effect when the ship's head is east or west, its maximum when the ship's head is north or south. This division of the semicircular deviation into two forces at right angles to each other, acting in the two great sections of the ship, is necessary to simplify investigation; for knowing the two forces, we can by simple rules combine them, and thus obtain the direction in the ship from which the whole polar force causing the semicircular deviation proceeds, as well as the total amount of this force.

The position in the ship from which the polar force may be considered as emanating, may be illustrated by the following figure 18,* representing eight iron ships, built respectively on the eight principal points of the compass. Keeping in view the principle referred to in a former page, that the compass needle *is attracted to that part of the ship which was south from the compass at the time of building*, we observe in each of the ships figured the position of the permanent south pole developed in the process of construction, marked thus •.

In the ship built head north, it will be seen the N end of the compass needle is drawn to a point on the stern immediately in a fore and aft line ; in the ship head N.E., to a point on the starboard quarter 45° from the fore and aft line ; in the ship head east, to a point on the starboard side abeam of the compass ; in the ship head S.E., to a point on the starboard bow 45° from the fore and aft line; in the ship'head south, to a point on the bow immediately in a fore and aft line; and so on, for the several remaining directions.

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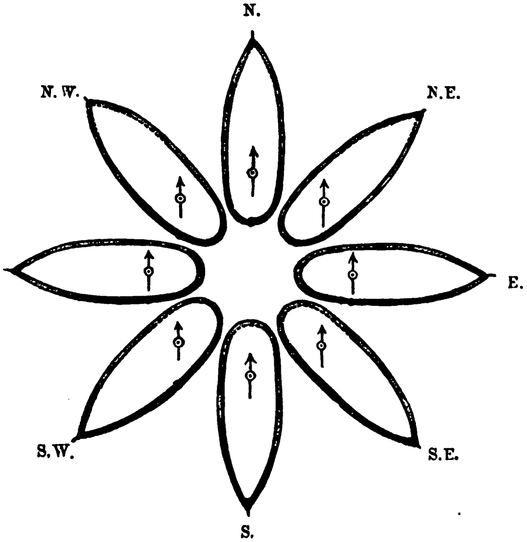
* In this deck-plan of the various ships, the portion of the top sides marked by a broken line indicates those parts which may be expected to repel the north end of the needle, *i. e.*, having north polarity or *red* magnetism. See also figures at p. 34, illustrative of the development of the two polarities in the process of building.

Fig. 18.



Assuming, as we have done, that the fore and aft force shall be represented by the co-efficient B, and with a + sign affixed, that it is a force drawing to the head of the ship (or easterly deviation produced, when the ship's head is east); and with a − sign affixed, that it is a force drawing to the stern (or westerly deviation produced, when the ship's head is east): also, that the co-efficient, C, shall represent the transverse force, and with a + sign affixed, that it is a force drawing to the starboard side of the ship (or easterly deviation produced, when the ship's head is north), and with a − sign affixed, that it is a force drawing to the port side of the ship (or westerly deviation produced, when the ship's head is north); it will be seen that the division of the polar force for each ship into its fore and aft and transverse parts, as represented by B and C, will stand thus:

In ship built head	North	the semicircular deviation will consist of;	all − B	no C	
,,	N.E.	,,	− B	+ C,	in equal parts
,,	East	,,	no B	all + C	
,,	S.E.	,,	+ B	+ C,	in equal parts
,,	South	,,	all + B	no C	
,,	S.W.	,,	+ B	− C,	in equal parts
,,	West	,,	no B	all − C	
,,	N.W.	,,	− B	− C,	in equal parts

The resultant of B and C is therefore the ship's polar force;* its direction being at that angle to the right of ship's head, of which the natural tangent is $\frac{C}{B}$ and its amount (or the maximum semicircular deviation) $\sqrt{B^2 + C^2}$.†

If, then, in our eight imaginary iron ships, the maximum semicircular deviation is assumed to be 20°, we shall have the following :—

		Co-efficients. B	Co-efficients. C	Spot in ship from which polar force emanates measured to *right* of ship's head ; or the "starboard angle."
In the ship built head	North	— 20°	0°	180°
,,	N.E.	— 14	+ 14	135
,,	East	0	+ 20	90
,,	S.E.	+ 14	+ 14	45
,,	South	+ 20	0	{ 0 360 }
,,	S.W.	+ 14	— 14	315
,,	West	0	— 20	270
,,	N.W.	— 14	— 14	225

or, if we wish to consider the force causing 20° of semicircular deviation, as the ship's horizontal force in terms of the earth's horizontal force considered as unity, or 1; we shall have the following, in which the force to ship's head and to starboard are the natural sines respectively of B and C, as expressed in degrees of deviation :—

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* See figure 6 of "parallelogram of forces," p. 37, where OP may be considered to represent the co-efficient B, and OQ (as drawn at right angles to OP) to represent C; then OR is the ship's polar force in amount, or $\sqrt{B^2 + C^2}$, and the angle $POR = \frac{PR}{OP} =$ nat. tan $\frac{C}{B}$. This is the modulus of the Astronomer-Royal (see *Phil. Trans.* 1856), a term used to denote the comparison between the ship's magnetic horizontal force, and the earth's horizontal force, the latter being considered as unity or 1.

† These values are readily obtained from the ordinary traverse table, as follows: Find B, expressed either in degrees and decimals of a degree (or its *natural sine*), in the latitude column, and similarly C in the departure column ; then the corresponding course is the *nat. tan* of $\frac{C}{B}$ or the "starboard angle" (see fig. 10); and the corresponding distance is $\sqrt{B^2 + C^2}$, or the maximum semicircular deviation, if B and C be taken in degrees; or the ship's polar force (in terms of the earth's horizontal force considered unity,) if B and C be entered with their *natural sines.*

		Ship's force to Head.	Ship's force to Starboard.	Ship's Horizontal Force.	
				Direction.	Amount.
In the ship built head	North	— ·342	0	180°	·342
„	N.E.	— ·243	+ ·243	135	„
„	East	0	+ ·342	90	„
„	S.E.	+ ·243	+ ·243	45	„
„	South	+ ·342	0	{ 0 360 }	„
„	S.W.	+ ·243	— ·243	315	„
„	West	0	— .342	270	„
„	N.W.	— ·243	— ·243	225	„

The co-efficients D and E represent the deviation caused by *horizontal* induction in soft iron, known as the "quadrantal."

E can only be caused by horizontal induction in soft iron unsymmetrically distributed, and is thus closely allied in character to a *real* A. At a compass in the middle line of the ship, where the soft iron is symmetrically distributed, it is, therefore, always very small in amount; but at a compass out of the middle line of the ship, as in the case illustrated by the iron spindle of a steering wheel, it will have a sensible value.* The maximum effect of E is on the four cardinal points, whilst the maximum effect of D, it will be remembered, is nearly on the inter-cardinal or quadrantal points.

D, which, it is seen, frequently assumes large values in iron-built ships of certain types, requires much attention on the part of the student to clearly apprehend its causes and effect. In ordinary cases it is always +, or *positive:* that is, it follows the signs + —, + — in the successive quadrants N.E., S.E., S.W., N.W. It is caused by horizontal induction in soft iron arranged according to one or other of the following types :—

Fig. 19.

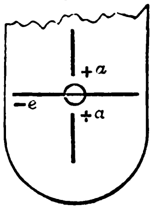
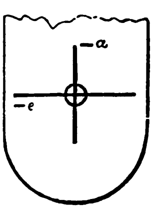


Fig. 20.



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* This is found especially to be the case in turret ships, when the compass by circumstances is placed near a turret and out of the middle line. At a compass so situated in H.M.S. Royal Sovereign, E was 9° with a D of 13°.

In these figures, $+a$ may be considered to represent masses of soft iron entirely before or entirely abaft the compass: as engines, boilers, funnels, iron masts, &c.

$-a$ to represent soft iron extending through the position of the compass: as the keel and hull of the ship, the screw shaft, armour plating, &c., and also the engines and boilers, if the compass is over them.

$-e$ to represent the effect of all the transverse soft iron: as the bottom of the ship, iron decks, iron beams, or engines and boilers.

$+e$ (not shown in figures, and of which there is no known instance) would represent the masses of iron, few in number, which lie to one side of the compass: as guns, davits, or where the compass is in or over a hatchway.

Of these types $+a$	will give as the ship swings round a	*positive**	quadrantal deviation
$-a$	”	*negative*	”
$-e$	”	*positive*	”
$+e$	”	*negative*	”

As a *positive* quadrantal deviation exists in all ordinary cases, we may infer that it is caused by the co-existence of the types $+a$ and $-e$, or the excess of $-e$ over $-a$; and as in every ship which has been examined $-e$ has a much larger value than $-a$, we may further infer that D is principally caused by horizontal induction in transverse iron of the type $-e$. This branch of the subject, relating to the separation of the quadrantal deviation into its two constituents—namely, that which arises from fore and aft induction, and that which arises from transverse induction—will be again referred to. [See Section VII.]

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* This is obvious from the following considerations:—

When north or south of the compass, the types or rods $+a$ produce no deviation, because they act in the direction in which the needle is pointing. When they are east or west of the compass they cease to be magnetic, and do not affect the direction of the needle. When they are to the N.E. or S.W. of the compass, then an easterly deviation of the needle is produced; and when to the N.W. or S.E., a westerly deviation.

SECTION VI.

On the calculations requisite to obtain the approximate co-efficients A, B, C, D, E, the exact co-efficients 𝔄, 𝔅, ℭ, 𝔇, 𝔈, and to form a deviation table from the co-efficients.

We have now arrived at that stage at which the subject may be treated numerically: for this purpose formulæ deduced from mathematical investigation of the phenomena already described must be employed; what, then, are the principles on which the application of mathematics to the deviation of the compass depends?

A. They are,

1st. That each portion of the ship's iron must be considered as either one or the other of the two extreme qualities known magnetically as "*hard*" iron or "*soft*" iron.

2nd. That the length of the needle is infinitesimally small, compared with the distance of the nearest attracting iron.

3rd. That the iron remains unchanged in position within the ship.

With regard to 1: As before described, "*hard*" iron is iron which, when once magnetised, retains its magnetism; "*soft*" iron is iron which has no independent magnetism, but when exposed to an inducing force it becomes instantly magnetised, with an intensity proportional to that of the inducing force, and when that force is removed it as instantly loses its magnetism. It must, however, be remembered that neither of these extreme conditions actually exist in nature; nevertheless the formulæ based upon them have been proved, by much experience, to satisfactorily represent every observed phenomenon, allowance being made for gradual changes in the values of the co-efficients they involve.

With regard to 2: In the general elevated position of a Standard compass, the ordinary sized needle of six and seven inches may be so considered with reference to the distance of the nearest iron; and the error of the assumption is almost entirely removed if the needle, instead of being a single bar one, consists of a system of four or of two needles, so arranged that with four parallel needles their extremities shall be 30° apart, or with two needles their extremities should be 60° apart.

How are the co-efficients A, B, C, D, E, numerically determined?

A. They are determined, by a simple calculation, and with much accuracy, from the deviations observed with the ship's head on a number of equidistant compass points round the circle—that is to say, from the deviations on the thirty-two points, or sixteen, or the eight principal compass points. Less accurate results for A, B, C, and E, can be obtained from the four cardinal compass points, and for A, B, C, and D, from the four intercardinal compass points N.E., S.E., S.W., N.W.

How are the principal co-efficients approximately determined at sight from a table of deviations?

A. In the following manner:

B is approximately the deviation at east; or the deviation at west with its sign changed,* or the mean of the two.

C is approximately the deviation at north; or the deviation at south with its sign changed, or the mean of the two.

D is the mean value of the deviations at N.E. and S.W.; or of the deviations at S.E. and N.W., with their signs changed, or of the mean of both these means.

A and E require the following simple calculation:—

For A, add algebraically† the deviations on the four cardinal compass points, or on any four equidistant compass points, and divide the sum by 4.

For E, take the deviations on the four cardinal compass points, reverse the signs of those at east and west, and divide the algebraical sum of the four deviations by 4.

The above will be found useful in practice, as affording a check to more detailed calculation.

Give an example of this from the table of H.M.S Achilles, see page 22.

Answer. B is approximately $+19^\circ\ 0'$ or $+18^\circ\ 0'$

or $+18\frac{1}{2}^\circ$

C is approximately $+1^\circ\ 40'$ or $-4^\circ\ 30'$

or $+3^\circ\ 5'$

D is approximately $\frac{1}{2}\left\{24^\circ\ 10' - 10^\circ\ 30'\right\}$

$= +6^\circ\ 50'$

or $\frac{1}{2}\left\{-6^\circ\ 0' + 19^\circ\ 30'\right\}$

$= +6^\circ\ 45'$

Mean $= +6\ \ 48$

A is approximately $\frac{1}{4}\left\{1^\circ\ 40' + 19^\circ\ 0' - 4^\circ\ 30' - 18^\circ\ 0'\right\}$

$= -0^\circ\ 27'$

E is approximately $\frac{1}{4}\left\{1^\circ\ 40' - 19^\circ\ 0' - 4^\circ\ 30' + 18^\circ\ 0'\right\}$

$= -0^\circ\ 57'$

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* *Note.*—Easterly deviations have always the + sign prefixed; westerly deviations the — sign.

† *i.e.*, add together all + quantities, and likewise all — quantities: subtract the least from the greatest, prefixing to the remainder the sign of the greatest.

Describe the process of computing the co-efficients from the deviations observed on the thirty-two points of the compass; taking for an example the deviation table of H.M.S. Achilles.

A. 1. Arrange the deviations in two columns, side by side. In the first column, the sixteen points from North to S. by E. by way of east; and in the second column, the sixteen points from South to N. by W. by way of west.*

Col. I.	Col. II.	Col. III.	Col. IV.
° ′	° ′	° ′	° ′
+ 1 40	— 4 30	— 1 25	+ 3 5
+ 9 20	— 6 0	+ 1 40	+ 7 40
+ 16 40	— 7 30	+ 4 35	+ 12 5
+ 22 0	— 9 0	+ 6 30	+ 15 30
+ 24 10	— 10 30	+ 6 50	+ 17 20
+ 24 30	— 12 20	+ 6 5	+ 18 25
+ 24 0	— 14 20	+ 4 50	+ 19 10
+ 22 0	— 16 0	+ 3 0	+ 19 0
+ 19 0	— 18 0	+ 0 30	+ 18 30
+ 15 50	— 19 50	— 2 0	+ 17 50
+ 12 50	— 20 50	— 4 0	+ 16 50
+ 9 0	— 21 0	— 6 0	+ 15 0
+ 6 0	— 19 30	— 6 45	+ 12 45
+ 2 0	— 16 30	— 7 15	+ 9 15
— 1 0	— 12 0	— 6 30	+ 5 30
— 3 20	— 5 30	— 4 25	+ 1 5

2. Form Col. III. by taking half the sum of the quantities in Cols. I. and II. [attending to the signs.]

3. Form Col. IV. thus: Change the signs of the quantities in Col. II. [mentally], and then take half the sum of the quantities in Cols. I. and II.

4. Prove the correctness of Cols. III. and IV. by seeing that the sum of the quantities on any line equals the quantity on the same line in Col. I.

The result arrived at in this stage of the computation is the separation of the "semicircular" from the other parts of the deviation, Col. IV. being the value of the semicircular deviation on all the points from North to S. by E. (by way of east); and the same with the signs changed being the value of the semicircular deviation on all the points from South to N. by W. (by way of west).

Col. III. is the "quadrantal" deviation combined with the "constant" deviation for the points from North to S. by E. (by way of east), and from South to N. by W. (by way of west).

[The regularity of the numbers in these columns will be seen, and is a good test of the accuracy of the observations.]

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* These are always to be understood as the points of direction of the ship's head by the Standard, or the compass actually observed. If the deviations are registered or observed, with the ship's head *correct* magnetic, such deviations must be converted into a deviation table, with ship's head given by compass. Napier's diagram affords the means for this conversion very readily.

Next multiply the values of the semicircular deviation, as given in Col. IV., by the natural sines of the rhumbs, *viz.*, 0, 11¼°, 22½°, 33¾° .... 78¾°, 90° (or .195, .383, .556, ... .981, 1.0), as represented by the symbols 0, S_1, S_2, S_3 .... S_7, 1, placed against each value;* so as to form Col. V., and by the natural cosines of the rhumbs, or, which is the same thing, by the natural sines of the rhumbs with 90° added, so as to form Col. VI.†

Finally, add all the + quantities in each column, and also the — quantities, subtract the least from the greatest, prefix the sign of the greatest, and divide by 8; the results from Cols. V. and VI. are the best possible values of B and C obtained from the observed deviations on each of the thirty-two points.

Col. IV.	Col. V. Computation of B.		Col. VI. Computation of C.	
° ′		° ′		° ′
+ 3 5	0	0 0	1	+ 3 5
+ 7 40	S_1	+ 1 30	S_7	+ 7 31
+ 12 5	S_2	+ 4 38	S_6	+ 11 10
+ 15 30	S_3	+ 8 37	S_5	+ 12 53
+ 17 20	S_4	+ 12 15	S_4	+ 12 15
+ 18 25	S_5	+ 15 19	S_3	+ 10 14
+ 19 10	S_6	+ 17 43	S_2	+ 7 20
+ 19 0	S_7	+ 18 38	S_1	+ 3 42
+ 18 30	1	+ 18 30	0	0 0
+ 17 50	S_7	+ 17 29	— S_1	— 3 29
+ 16 50	S_6	+ 15 33	— S_2	— 6 27
+ 15 0	S_5	+ 12 28	— S_3	— 8 20
+ 12 45	S_4	+ 9 1	— S_4	— 9 1
+ 9 15	S_3	+ 5 8	— S_5	— 7 41
+ 5 30	S_2	+ 2 6	— S_6	— 5 5
+ 1 5	S_1	+ 0 13	— S_7	— 1 4
Sum of + terms		+ 159 8		+ 68 10
Sum of — terms				— 41 7
		+ 159 8		+ 27 3
	8		8	
	B =	+ 19 54	C =	+ 3 23

---

* The mathematical expression for the semicircular deviation, is B sin ζ' + C cos ζ', ζ' being the "compass course" or azimuth of the ship's head, from the direction of the disturbed needle, reckoned + to the eastward, — to the westward.

The arrangement of the multipliers, or symbols, 0, S_1, S_2 ...... S_7, 1, it will be seen, represents the *sine* of the azimuth of ship's head for determining the mean value of B; and the reverse arrangement 1, S_7, S_6, ... S_1 0, represents the *cosine* of the azimuth of ship's head for determining the mean value of C. A table of multipliers extending to 39° of deviation will be found at the end, p. 132. The ordinary traverse table, as arranged for the points of the compass, to be found in most navigation treatises, can also be used for obtaining the required values.

† In these multiplications, the rule of signs must be carefully attended to, namely :—

+ multiplied by + has the sign +
— „ — „ +
+ „ — „ —
— „ + „ —

We have stated that Col. III. is the quadrantal deviation, combined with the constant deviation ;—the process of finding separately the co-efficients A, D, E, is of the same form as that employed in finding B and C, namely :—

Write down the upper half of Col. III. now as Col. Ia., and the lower half of Col. III. now as Col. IIa. ; from these form Cols. IIIa. and IVa., in the same manner as the former Cols. III. and IV., proving their correctness also in the same way.

Col. Ia.	Col. IIa.	Col. IIIa.	Col. IVa.
° ′	° ′	° ′	° ′
− 1 25	+ 0 30	− 0 28	− 0 57
+ 1 40	− 2 0	− 0 10	+ 1 50
+ 4 35	− 4 0	+ 0 17	+ 4 18
+ 6 30	− 6 0	+ 0 15	+ 6 15
+ 6 50	− 6 45	+ 0 2	+ 6 48
+ 6 5	− 7 15	− 0 35	+ 6 40
+ 4 50	− 6 30	− 0 50	+ 5 40
+ 3 0	− 4 25	− 0 42	+ 3 42
	Sum of + terms	+ *0 34*	
	Sum of — terms	— *2 45*	
		— *2 11*	
	8		
	A =	— *0 16*	

Col. IIIa. is the "constant" part of the deviation, each of the eight values being derived from four points of the compass 90° from each other, as N. by E., E. by S., S. by W., W. by N., &c. The sum of these divided by 8 gives the best value of A.

Col. IVa. is the "quadrantal" deviation on the points from N. to E. and from S. to W. ; and with the signs changed the quadrantal deviation from E. to S. and from W. to N.

By now multiplying each value of the quadrantal deviation in Col. IVa. by the natural sines of the rhumbs 0, S_2, S_4, S_6, 1*, we get in Col. Va., by dividing their sum by 4, the mean value of D ; and similarly by multiplying by the natural cosines of the rhumbs 1, S_6, S_4, S_2, and dividing their sum by 4, we get in Col. VIa. the mean value of E.

Col. IVa.	Col. Va. Computation of D.		Col. VIa. Computation of E.	
° ′		° ′		° ′
— 0 57	0	*0 0*	1	— *0 57*
+ 1 50	S_2	+ *0 42*	S_6	+ *1 42*
+ 4 18	S_4	+ *3 3*	S_4	+ *3 3*
+ 6 15	S_6	+ *5 46*	S_2	+ *2 24*
+ 6 48	1	+ *6 48*	0	*0 0*
+ 6 40	S_6	+ *6 10*	— S_2	— *2 33*
+ 5 40	S_4	+ *4 0*	— S_4	— *4 0*
+ 3 42	S_2	+ *1 25*	— S_6	— *3 25*
Sum of + terms		+ *27 54*		+ *7 9*
Sum of — terms				— *10 55*
		+ *27 54*		— *3 46*
	4		4	
	D =	+ *6 58*	E =	— *0 56*

---

* The mathematical expression for the quadrantal deviation is D sin 2♈+E cos 2♈. The arrangement of the multipliers 0, S_2, S_4, S_6, 1, &c., it will be seen, represents the *sine* of twice the azimuth of ship's head for determining the mean value of D ; and the reverse arrangement, 1, S_6, S_4, S_2, &c., the *cosine* of twice the azimuth of ship's head for determining the mean value of E.

How are the values of the co-efficients determined from *sixteen* points?

Answer.

Col. I. is formed from the eight equidistant points N., N.N.E. to S.S.E.

Col. II. is formed from the eight equidistant points S., S.S.W. to N.N.W.

Then proceeding as in the case of thirty-two points—but omitting the multipliers S_1, S_3, S_5, S_7, as no longer required—the sums of Cols. V. and VI. are now divided by 4 instead of 8.

Similarly the sum of the "constant" deviation is divided by 4.—

Col. IVa. of the quadrantal deviation has the alternate rhumbs S_4 and 1 affixed to form Cols. Va. and VIa.; and the sums of these columns are divided by 2.

Cols. I.	II.	III.	IV.		V.		VI.
° ′	° ′	° ′	° ′		° ′		° ′
+ 1 40	− 4 30	−1 25	+ 3 5	0	0 0	1	+ 3 5
+16 40	− 7 30	+4 35	+12 5	S_2	+ 4 38	S_6	+11 10
+24 10	−10 30	+6 50	+17 20	S_4	+12 15	S_4	+12 15
+24 0	−14 20	+4 50	+19 10	S_6	+17 43	S_2	+ 7 20
+19 0	−18 0	+0 30	+18 30	1	+18 30	0	0 0
+12 50	−20 50	−4 0	+16 50	S_6	+15 33	$-S_2$	− 6 27
+ 6 0	−19 30	−6 45	+12 45	S_4	+ 9 1	$-S_4$	− 9 1
− 1 0	−12 0	−6 30	+ 5 30	S_2	+ 2 6	$-S_6$	− 5 5
			Sum of + terms		+79 46		+33 50
			Sum of − terms		—		−20 33
					+79 46		+13 17
				B $\overset{4}{=}$	+19 56	C $\overset{4}{=}$	+ 3 19

Cols. Ia.	IIa.	IIIa.	IVa.		Va.		VIa.
° ′	° ′	° ′	° ′		° ′		° ′
− 1 25	+ 0 30	− 0 28	− 0 57	0	0 0	1	− 0 57
+ 4 35	− 4 0	+ 0 17	+ 4 18	S_4	+ 3 3	S_4	+ 3 3
+ 6 50	− 6 45	+ 0 2	+ 6 48	1	+ 6 48	0	0 0
+ 4 50	− 6 30	− 0 50	+ 5 40	S_4	+ 4 0	$-S_4$	− 4 0
		+ 0 19			+13 51		+ 3 3
		− 1 18			—		− 4 57
		− 0 59			+13 51		− 1 54
	A $\overset{4}{=}$	− 0 15		D $\overset{2}{=}$	+ 6 56	E $\overset{2}{=}$	− 0 57

How are the values of the co-efficients determined from *eight* points?

Answer.

Col. I. is formed from the four equidistant points North, N.N.E., East, S.E.

Col. II. is formed from the four equidistant points South, S.S.W., West, N.W.

The multipliers S_4 and 1 are alone employed, and the sums of Cols. V. and VI. are divided by 2.

The sum of the constant deviation is divided by 2.

E becomes the upper line of Col. IVa.

D becomes the lower line of Col. IVa.

Cols. I.	II.	III.	IV.		V.		VI.
° ′	° ′	° ′	° ′		° ′		° ′
+ 1 40	− 4 30	−1 25	+ 3 5	0	0 0	1	+ 3 5
+24 10	−10 30	+6 50	+17 20	S_4	+12 15	S_4	+12 15
+19 0	−18 0	+0 30	+18 30	1	+18 30	0	0 0
+ 6 0	−19 30	−6 45	+12 45	S_4	+ 9 1	$-S_4$	− 9 1
			Sum of + terms		+39 46		+15 20
			Sum of − terms		—		− 9 1
					+39 46		+ 6 19
				B $\overset{2}{=}$	+19 53	C $\overset{2}{=}$	+ 3 10

Ia.	IIa.	IIIa.	IVa.
° ′	° ′	° ′	° ′
−1 25	+0 30	−0 28	−0 57 = E
+6 50	−6 45	+0 2	+6 48 = D
		−0 26	
	A $\overset{2}{=}$	−0 13	

We are now enabled to form an opinion as to the degree of approximation of the several results.

	A	B	C	D	E
	° ′	° ′	° ′	° ′	° ′
From 32 equidistant points we obtain for	—0 16	+19 54	+3 23	+6 58	—0 56
„ 16 „ „ „	—0 15	+19 56	+3 19	+6 56	—0 57
„ 8 „ „ „	—0 13	+19 53	+3 10	+6 48	—0 57
„ 4 cardinal points (see *ante*, p. 55)	—0 27	+18 30	+3 5	—*	—0 57
„ 4 inter-cardinal points†	+0 2	+21 16	+3 14	+6 48	—*

Do the co-efficients A, B, C, D, E, as denoted by Roman letters, represent the exact value of the deviations observed under all circumstances?

A. No; the formulæ from which they are derived are only approximate, and though the approximation is close when the deviations are moderate in amount, the errors increase as the square of the deviations. Thus, if with a maximum deviation of 7°, they are 10′ in error, with a deviation of 21°, they will be about 1° 30′ in error; hence, when the maximum deviation on any course much exceeds 20°, it is necessary to use instead of A, B, C, D, E, what are known as the exact co-efficients—the exact co-efficients being distinguished by the German letters $\mathfrak{A}$, $\mathfrak{B}$, $\mathfrak{C}$, $\mathfrak{D}$, $\mathfrak{E}$, and being *nearly* the natural sines of the angles A, B, C, D, E.

How are the exact co-efficients $\mathfrak{A}$, $\mathfrak{B}$, $\mathfrak{C}$, $\mathfrak{D}$, $\mathfrak{E}$, determined?

A. When A, B, C, D, E, are known by the ship being completely swung, the exact co-efficients may be derived from the following simple formulæ and calculation, which are sufficiently exact for deviations not exceeding 40°.

$$\mathfrak{A} = \sin A$$

$$\mathfrak{B} = \sin B \times (1 + \tfrac{1}{2} \sin D + \tfrac{1}{12} \operatorname{versin} B - \tfrac{1}{4} \operatorname{versin} C) + \tfrac{1}{2} \sin C \times \sin E$$

$$\mathfrak{C} = \sin C \times (1 - \tfrac{1}{2} \sin D - \tfrac{1}{4} \operatorname{versin} B + \tfrac{1}{12} \operatorname{versin} C) + \tfrac{1}{2} \sin B \times \sin E$$

$$\mathfrak{D} = \sin D \times (1 + \tfrac{1}{3} \operatorname{versin} D)$$

$$\mathfrak{E} = \sin E - \sin A \times \sin D$$

---

* D cannot be determined from deviations observed on the four cardinal points, or E from deviations observed on the four inter-cardinal points.

† Found as follows :—

Ship's head	I.	Ship's head	II.	III.	IV.	V.	
	° ′		° ′	° ′	° ′	°	
N.E.	+24 10	S.W.	—10 30	+6 50	+17 20 S_4	+12 15	Sum Col. V.=B +21 16,
S.E.	+ 6 0	N.W.	—19 30	—6 45	+12 45 S_4	+ 9 1	

½ sum of terms, Col. III. +0 2 = A

Ditto changing sign 2nd term +6 48 = D

{Changing sign of 2nd term, Col. V.} =C + 3 14.

Example of calculation.

	A	B	C	D	E	
H.M.S. Achilles, Oct. 13, 1864.	−0° 16′	+19° 54′	+3° 23′	+6° 58′	−0° 56′	From 32 points.
sin	−.005	+.340	+.059	+.121	−.016	
versin		.059	.002	.007		

$$\mathfrak{B} = +.340\times(1+.061+.005-.000)+\tfrac{1}{2}(.059\times-.016)$$
$$= +.340\times1.066+(-.001)$$
$$= +.362$$
$$\mathfrak{C} = +.059\times(1-.061-.015+.000)+\tfrac{1}{2}(.340\times-.016)$$
$$= +.059\times.924+(-.003)$$
$$= +.051$$
$$\mathfrak{D} = +.121=(1+.002)$$
$$= +.121$$
$$\mathfrak{E} = -.016-(.005\times.121)$$
$$= -.016$$

How are the exact co-efficients determined, without first knowing A, B, C, D, E?

Answer.

1. $\mathfrak{A}$, $\mathfrak{B}$, $\mathfrak{C}$, $\mathfrak{D}$, $\mathfrak{E}$ can be derived from the deviations observed on the eight principal compass points.
2. $\mathfrak{A}$, $\mathfrak{B}$, $\mathfrak{C}$, —, $\mathfrak{E}$,, ,, ,, four cardinal compass points.
3. $\mathfrak{A}$, $\mathfrak{B}$, $\mathfrak{C}$, $\mathfrak{D}$, — ,, ,, ,, four quadrantal compass points.
4. —, $\mathfrak{B}$, $\mathfrak{C}$, $\mathfrak{D}$, — ,, ,, ,, on the principal compass points in one semicircle.
5. —, $\mathfrak{B}$, $\mathfrak{C}$, $\mathfrak{D}$, — ,, ,, ,, on two adjacent cardinal points, and the intermediate quadrantal compass point.
6. —, $\mathfrak{B}$, $\mathfrak{C}$, $\mathfrak{D}$, — ,, ,, ,, on any three compass courses.

Of these methods, 1, 2, and 3, are the best to employ when the deviations exceed 40°.*

Methods 4 and 5, but especially the latter, are very useful in practice; for, as it is found that the co-efficients $\mathfrak{A}$ and $\mathfrak{E}$ are always small in a good compass, when placed in the middle fore and aft line of the ship, we may neglect their consideration under such conditions without any great sacrifice of accuracy in the results.† The computation of $\mathfrak{B}$, $\mathfrak{C}$, $\mathfrak{D}$, from the deviation observed on any three courses, is complicated.‡

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* As the computation is complicated, and except in very exceptional cases, such as between decks in armour-plated ships, or near gun turrets, no compass should be so placed as to indicate this enormous amount of deviation, it has not been considered desirable to swell this work with the formulæ and illustrative examples. The student is therefore referred to the Admiralty Manual.

† As in swinging a ship through a semicircle two determinations by method 5 can be obtained, the formula and calculations for the semicircle have been omitted. The student will of course refer to the Admiralty Manual for the formula, if required. The seaman will readily understand the ease with which a ship's head can be turned through a quadrant, without seriously affecting the progress of the voyage.

‡ Method 6 has not been comprised in this work. The student is again referred to the Admiralty Manual.

Describe, by formulæ and examples, how $\mathfrak{B}$, $\mathfrak{C}$, $\mathfrak{D}$, are obtained by swinging the ship through a single quadrant.

A. In this case it is necessary to have *very exact* observations of deviation made on the three principal points in the quadrant; that is, on two adjacent cardinal points and the intermediate quadrantal point: and to assume $\mathfrak{A}$ and $\mathfrak{E}$ to be zero. [The symbols N.E δ, N δ, E δ, &c., in these formulæ, represent the deviation (δ) with the ship's head respectively N.E., North, East, &c., by compass.]

Formulæ.

N.E. Quadrant. $\mathfrak{D}=\dfrac{\sin 45^\circ\times\sin \text{N.E}\,\delta-\frac{1}{2}(\sin \text{N}\,\delta+\sin \text{E}\,\delta)}{\sin 45^\circ\times\cos \text{N.E}\,\delta-\frac{1}{2}(\sin \text{N}\,\delta-\sin \text{E}\,\delta)}$ $\mathfrak{B}=(1+\mathfrak{D})\sin \text{E}\,\delta$ $\mathfrak{C}=(1-\mathfrak{D})\sin \text{N}\,\delta$

S.E. Quadrant. $\mathfrak{D}=\dfrac{-\sin 45^\circ\times\sin \text{S.E}\,\delta+\frac{1}{2}(\sin \text{E}\,\delta+\sin \text{S}\,\delta)}{\sin 45^\circ\times\cos \text{S.E}\,\delta-\frac{1}{2}(\sin \text{E}\,\delta-\sin \text{S}\,\delta)}$ $\mathfrak{B}=(1+\mathfrak{D})\sin \text{E}\,\delta$ $\mathfrak{C}=-(1-\mathfrak{D})\sin \text{S}\,\delta$

S.W. Quadrant. $\mathfrak{D}=\dfrac{\sin 45^\circ\times\sin \text{S.W}\,\delta-\frac{1}{2}(\sin \text{S}\,\delta+\sin \text{W}\,\delta)}{\sin 45^\circ\times\cos \text{S.W}\,\delta-\frac{1}{2}(\sin \text{S}\,\delta-\sin \text{W}\,\delta)}$ $\mathfrak{B}=-(1+\mathfrak{D})\sin \text{W}\,\delta$ $\mathfrak{C}=-(1-\mathfrak{D})\sin \text{S}\,\delta$

N.W. Quadrant $\mathfrak{D}=\dfrac{-\sin 45^\circ\times\sin \text{N.W}\,\delta+\frac{1}{2}(\sin \text{W}\,\delta+\sin \text{N}\,\delta)}{\sin 45^\circ\times\cos \text{N.W}\,\delta-\frac{1}{2}(\sin \text{W}\,\delta-\sin \text{N}\,\delta)}$ $\mathfrak{B}=-(1+\mathfrak{D})\sin \text{W}\,\delta$ $\mathfrak{C}=(1-\mathfrak{D})\sin \text{N}\,\delta$

*Examples of working the Formulæ.**

			δ	sin	cos		δ	sin	cos
From table, H.M.S. Achilles.	Head by compass	North	+ 1° 40′	+.029		South	— 4° 30′	—.078	
	„	N.E	+24 10	+.409	+.912	S.W	—10 30	—.182	+.983
	„	East	+19 0	+.326		West	—18 0	—.309	
	„	S.E	+ 6 0	+.104	+.995	N.W	—19 30	—.334	+.943

N.E. Quadrant. $\mathfrak{D}=\dfrac{.707\times.409-\frac{1}{2}(+.029+.326)}{.707\times.912-\frac{1}{2}(+.029-.326)}$ $\mathfrak{B}=1.139\times.326$ $\mathfrak{C}=.861\times.029$

$=\dfrac{.289-.178}{.645-(-.149)}=\dfrac{.111}{.794}=+.139$ $=+.371$ $=+.025$

S.E. Quadrant. $\mathfrak{D}=\dfrac{-.707\times.104+\frac{1}{2}(+.326+(-.078))}{.707\times.995-\frac{1}{2}(+.326-(-.078))}$ $\mathfrak{B}=1.102\times.326$ $\mathfrak{C}=-.898\times-.078$

$=\dfrac{-.073+.124}{.703-.202}=\dfrac{.051}{.501}=+.102$ $=+.359$ $=+.070$

S.W. Quadrant. $\mathfrak{D}=\dfrac{.707\times-.182-\frac{1}{2}(-.078+(-.309))}{.707\times.983-\frac{1}{2}(-.078-(-.309))}$ $\mathfrak{B}=-1.110\times-.309$ $\mathfrak{C}=-.890\times-.078$

$=\dfrac{-.129-(-.193)}{.695-.115}=\dfrac{.064}{.580}=+.110$ $=+.343$ $=+.069$

N.W. Quadrant. $\mathfrak{D}=\dfrac{-.707\times-.334+\frac{1}{2}(-.309+.029)}{.707\times.943-\frac{1}{2}(-.309-.029)}$ $\mathfrak{B}=-1.115\times-.309$ $\mathfrak{C}=.885\times.029$

$=\dfrac{.236+(-.140)}{.667-(-.169)}=\dfrac{.096}{.836}=+.115$ $=+.344$ $=+.026$

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* In these computations the algebraic rule of signs must be carefully attended to. See also foot-note, p. 72.

As it is often in practice found to be extremely useful to construct a table of deviations from the known co-efficients, explain how this converse operation is performed; employing the co-efficients of H.M.S. Achilles as just determined, and restricting the computation, for convenience, to sixteen points.

A. There are two methods of performing this operation according as we have given A, B, C, D, E, or 𝔄, 𝔅, ℭ, 𝔇, 𝔈: we shall first suppose A, B, C, D, E to be given. Arrange in four parallel columns the co-efficients B, C, D, E, with their signs affixed, as in the annexed example: further, arrange vertically below B, the multipliers representing the *natural sines* of the eight even rhumbs from North to S.S.E.: below C, the multipliers representing the *natural cosines* of the same eight rhumbs: below D, the multipliers representing *the sines* of twice the same rhumbs: and below E, *the cosines* of twice the same rhumbs.

Then perform the multiplication indicated. The algebraic sum of the four products on any line is the deviation due to that point.*

For the convenience of working, this algebraic sum is most easily obtained, by computing separately the semicircular and quadrantal deviation (see example), as then for the remaining eight even points of the compass, from South to N.N.W., we have only to bring down the semicircular deviation obtained from the points from North to S.S.E., and *change the signs;* as also the quadrantal deviation in the same order, *without* changing the signs; and by summing these quantities the whole table of deviations is consequently formed.

The co-efficient A, being a constant quantity, must be algebraically applied throughout to each value.

Example.—To form an approximate Deviation table, H.M.S. Achilles, from co-efficients A, B, C, D, E.

	B		C		D		E		Sum of B & C (a)	Sum of D & E (b)	Sum of a & b	A	Deviation
		+19° 54′		+3° 23′		+6° 58′		−0° 56′					
North	0	0 0	o	+3 23	0	0 0	1	−0 56	+ 3° 23′	−0° 56′	+ 2° 27′	−0° 16′	+ 2° 11
N.N.E.	S_2	+ 7 37	S_6	+3 8	S_4	+4 56	S_4	−0 40	+10 45	+4 16	+15 1		+14 45
N.E.	S_4	+14 4	S_4	+2 25	1	+6 58	o	0 0	+16 29	+6 58	+23 27		+23 11
E.N.E.	S_6	+18 23	S_2	+1 17	S_4	+4 56	$-S_4$	+0 40	+19 40	+5 36	+25 16		+25 0
East	1	+19 54	o	0 0	0	0 0	−1	+0 56	+19 54	+0 56	+20 50		+20 34
E.S.E.	S_6	+18 23	$-S_2$	−1 17	$-S_4$	−4 56	$-S_4$	+0 40	+17 6	−4 16	+12 50		+12 34
S.E.	S_4	+14 4	$-S_4$	−2 25	−1	−6 58	o	0 0	+11 39	−6 58	+ 4 41		+ 4 25
S.S.E.	S_2	+ 7 37	$-S_6$	−3 8	$-S_4$	−4 56	S_4	−0 40	+ 4 29	−5 36	− 1 7		− 1 23
South	For these points repeat Col. (a), but *change the signs.*								− 3 23	−0 56	− 4 17		− 4 33
S.S.W.									−10 45	+4 16	− 6 29		− 6 45
S.W.									−16 29	+6 58	− 9 31		− 9 47
W.S.W									−19 40	+5 36	−14 4		−14 20
West	Also, repeat Col. (b), *without* changing the signs.								−19 54	+0 56	−18 58		−19 14
W.N.W									−17 6	−4 16	−21 22		−21 38
N.W.									−11 39	−6 58	−18 37		−18 53
N.N.W									− 4 29	−5 36	−10 5		−10 21

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* In other words, this is the computation of the formula—

$$\delta = A + B \sin \zeta + C \cos \zeta + D \sin 2\zeta + E \cos 2\zeta,$$

δ, being the deviation reckoned + when the north end of the needle is drawn to the east, — when drawn to the west.

If we have $\mathfrak{B}$, $\mathfrak{C}$, $\mathfrak{D}$ given (considering $\mathfrak{A}$ and $\mathfrak{E}$ zero), an *exact* table of deviations may be computed by the following method :—

For a first approximation.

Compute $\mathfrak{B} \sin \zeta + \mathfrak{C} \cos \zeta + \mathfrak{D} \sin 2\zeta$ for the sixteen points by a form similar to those just given. This will give a first approximation to the natural sines of the deviations on those points, which will be,—right on the quadrantal points ;

too small (numerically) in the N. and S. quadrants ;
too large (numerically) in the E. and W. quadrants.

For corrections at N. and S.

Let $\frac{1}{\mathfrak{D}} = n$: then add to first approximation at N. and S.

$\frac{1}{n}$th of first approximation, for first correction,

$\frac{1}{n}$th of first correction, for second correction,

these corrections being added numerically.

For corrections at E. and W.

The rule is the same, but the first correction is *subtracted.*
" " second correction is *added.*

Corrections at N.N.W., N.N.E., S.S.E., S.S.W.

The rule is the same as at N. and S., only the factor is $\frac{S_4}{n} = \frac{.707}{n}$.

Corrections at E.N.E., E.S.E., W.S.W., W.N.W.

The rule is the same as at E. and W., only the factor is $\frac{S_4}{n} = \frac{.707}{n}$.

Finally, find the angles of which these results are the sines. These will be *very nearly* the correct deviations.*

Example.—To form an exact Deviation table, H.M.S. Achilles, from co-efficients $\mathfrak{B}$, $\mathfrak{C}$, $\mathfrak{D}$.

Multipliers for $\mathfrak{B}$, $\mathfrak{C}$, $\mathfrak{D}$.
$S_2 = .384$, $S_4 = .707$, $S_6 = .924$

$$n = \frac{1}{\mathfrak{D}} = \frac{1}{.121} = 8.3, \quad \frac{1}{n} = \frac{1}{8}\text{th.}$$

$$\frac{S_4}{n} = \frac{.707}{n} = \frac{.707}{8.8} = .085 = \frac{1}{12}\text{th.}$$

	$\mathfrak{B}$ +.362		$\mathfrak{C}$ +.051		$\mathfrak{D}$ +.121		Sum of $\mathfrak{B}$ and $\mathfrak{C}$ (a)	Sum of $\mathfrak{B}$, $\mathfrak{C}$, $\mathfrak{D}$, first approximation.	Correction.		Deviation.			
									First.	Second.		°	′	
North.	0	.0	1	+.051	0	.0	+.051	+.051	+.006	+.001	=+.058 or	3	20	E.
N.N.E.	S_2	+.138	S_6	+.047	S_4	+.085	+.185	+.270	+.022	+.002	=+.294	17	5	–
N.E.	S_4	+.256	S_4	+.036	1	+.121	+.292	+.413			=+.413	24	25	–
E.N.E.	S_6	+.335	S_2	+.019	S_4	+.085	+.354	+.439	—.037	+.003	=+.405	23	55	–
East.	1	+.362	0	.0	0	.0	+.362	+.362	—.045	+.006	=+.323	18	50	–
E.S.E.	S_6	+.335	$-S_2$	—.019	$-S_4$	—.085	+.316	+.231	—.020	+.002	=+.213	12	15	–
S.E.	S_4	+.256	$-S_4$	—.036	— 1	—.121	+.220	+.099			=+.099	5	40	–
S.S.E.	S_2	+.139	$-S_6$	—.047	$-S_4$	—.085	+.092	+.007	+.001		=+.008	0	30	–
South.	For these points repeat Col. (a), but *change the signs.*					.0	—.051	—.051	—.006	—.001	=—.058	3	20	W.
S.S.W.						+.085	—.185	—.100	—.008	—.001	=—.109	6	15	–
S.W.						+.121	—.292	—.171			=—.171	9	50	–
W.S.W.						+.085	—.354	—.269	+.022	—.002	=—.249	14	25	–
West.	Also repeat Col. $\mathfrak{D}$,. *without* changing the signs.					.0	—.362	—.362	+.045	—.006	=—.323	18	50	–
W.N.W.						—.085	—.316	—.401	+.033	—.003	=—.371	21	45	–
N.W.						—.121	—.220	—.341			=—.341	20	0	–
N.N.W.						—.085	—.092	—.177	—.015	—.001	=—.193	11	10	–

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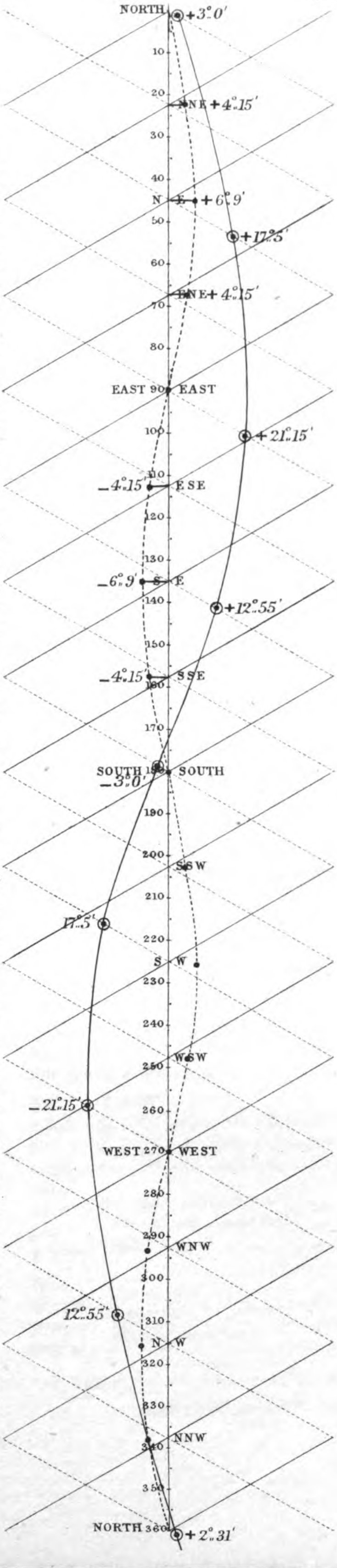
* This is the computation of the more exact formula—

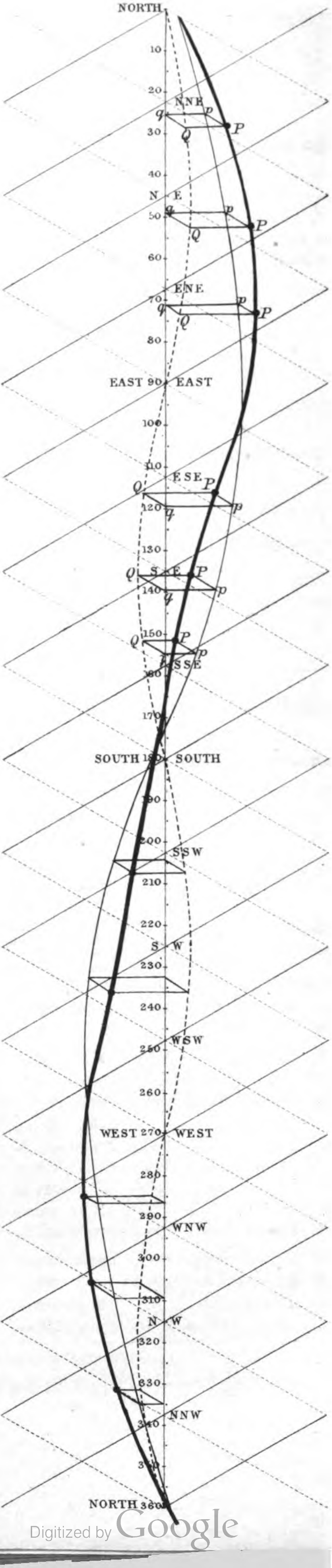
$$\sin \delta = \{\mathfrak{B} \sin \zeta + \mathfrak{C} \cos \zeta + \mathfrak{D} \sin 2\zeta\}\{1 + \mathfrak{D} \cos 2\zeta + (\mathfrak{D} \cos 2\zeta)^2\}$$

CURVE of DEVIATIONS obtained by Graphic Method.

The Coefficients 𝔅. ℭ. 𝔇 being given. 𝔄 and 𝔈 assumed as Zero.



1. Example. H.M.S. Achilles. Quadrantal Curve shewn by broken line. Curve of Semicircular deviation by Continuous line.



2. Example. H.M.S. Achilles, continued. Combination of Quadrantal and Semicircular Curves: resulting Curve of Deviations in thick line.

Can we, by any simple method, obtain a curve of deviations, if the co-efficients are given, and thus either neglect or verify the computation as may be wished?

A. Yes, there are several ingenious graphic methods; but that by the employment of Napier's diagram will be found, perhaps, the most simple and convenient in practice. Having $\mathfrak{B}$, $\mathfrak{C}$, $\mathfrak{D}$ (assuming $\mathfrak{A}$ and $\mathfrak{E}$ to be zero), expressed as the degrees of which, $\mathfrak{B}$, $\mathfrak{C}$, $\mathfrak{D}$ are the natural sines, we must proceed in the following manner:

With the diagram placed vertically, construct (see Plate II.)—

First. The quadrantal curve.

This is done by taking from the vertical scale of degrees an arc equal to $\mathfrak{D}$ multiplied by sin 60°, or .886 $\mathfrak{D}$

(in the annexed figure of curve of Achilles $= +.121 \times .886 = .107 = 6°9'$ in arc.)

This distance is then to be laid off perpendicularly to the central line of the diagram at the four quadrantal points: to the right at N.E. and S.W., to the left at S.E. and N.W.

Next with an arc equal to $\mathfrak{D}.\ \sin 60° \times \sin 45°$, or $.886\ \mathfrak{D} \times .707 = .612\ \mathfrak{D}$

(in the annexed figure $+ .121 \times .612 = .074 = 4°\ 15'$ in arc)

laid off at the eight semi-quadrantal points also perpendicularly to the central line: to the right in the 1st and 3rd quadrants, to the left in the 2nd and 4th quadrants.

Through these twelve points, and the N. E. S. W. N. points on the central line, the quadrantal curve is readily drawn.

Secondly. Construct the curve of semicircular deviation by laying down along the *dotted lines*, $\mathfrak{C}$ at North, $\mathfrak{B}$ at East: $-\mathfrak{C}$ at South, and $-\mathfrak{B}$ at West.

Along the N.E. dotted line the arc $\mathfrak{B} \times \sin 45° + \mathfrak{C} \times \sin 45°$
" S.E. " $\mathfrak{B} \times \sin 45° - \mathfrak{C} \times \sin 45°$
" S.W. " $\mathfrak{B} \times -\sin 45° - \mathfrak{C} \times \sin 45°$
" N.W. " $\mathfrak{B} \times -\sin 45° + \mathfrak{C} \times \sin 45°$

and through the eight points thus determined draw the semicircular curve.

(In the annexed figure $\mathfrak{B} = + .362 = 21°\ 15'$ in arc.)
$\mathfrak{C} = + .051 = 3°\ 0'$ in arc.)

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or $= \dfrac{\mathfrak{B} \sin \zeta' + \mathfrak{C} \cos \zeta' + \mathfrak{D} \sin 2\zeta'}{1 - \mathfrak{D} \cos 2\zeta'}$ to terms of third order inclusive (see Admiralty Manual, 3rd Ed. p. 113), which, as is seen, is easily calculated, as $\mathfrak{D} \cos 2\zeta'$, if we take ζ' at intervals of two points, has only two numerical values, *viz.*, $\mathfrak{D}$ and $\mathfrak{D}s_4$, each of small value. These, applied as multipliers to the sum of the quantities within the first brackets, give the first correction, and, applied as multipliers to the first correction, give the second correction, and so on, though it is seldom, if ever, necessary to go further.

Distance for N.E. dotted line = 21°.2 × .707 + 3°.0 × .707
= 15°.0 + 2°.1 = +17°.1
„ S.E. „ = 15°.0 — 2°.1 = +12°.9
„ S.W. „ = 15°.0 — 2°.1 = —17°.1
„ N.W. „ = 15°.0 + 2°.1 = —12°.9

Thirdly. To combine the two curves, or rather to superpose the quadrantal on the semicircular curve, proceed thus:—From any point *Q* in the quadrantal curve draw a line parallel to the dotted lines intersecting the central line in *q*. From *q* draw a line perpendicular to the central line intersecting the semicircular curve in *p*, then complete the parallelogram *Q q p P*. *P* is a point in the desired Napier's curve. The curve being drawn, the deviations are obtained in the usual way. (See pages 18—23.)

SECTION VII.

On the determination of the directive force on board ship and of the co-efficient λ (lambda)—*On the connection also between* λ *and* $\mathfrak{D}$.

Is it not the case that in nearly all the iron ships examined, a diminution of the mean directive force of the compass needle has been found?

A. Such is the case; and, under some conditions, to a very large amount. For example, on the main deck of iron armoured vessels it is commonly reduced one-fourth from its value on shore, or in a wood-built ship—that is to three-fourths of its proper value; and at the Standard compass of ordinary iron ships it is commonly reduced one-seventh, or to six-sevenths of its proper value.

What is the effect of this observed law of decrease of directive force on the observed deviations?

A. That of indirectly increasing them by increasing the effect of all the disturbing forces on board, which arise from friction or imperfect workmanship;* as well as those which arise from permanent magnetism.

How do you explain this general effect of the diminution of directive forces of the compass needle in iron ships?

A. We have seen in Section IV. pp. 35, 36, that the effect of a permanent magnet in revolving round a compass is not only to cause a semicircular deviation, but to increase or decrease the directive force of the needle as it acts in conjunction with or antagonistic to the earth's horizontal force. In the complete revolution of the magnet, however, the increase and decrease of the directive force of the needle due to each 180° of the magnet's revolution are equal in amount; so that, if we consider the earth's horizontal force $= 1$, the mean of the directive forces of the needle for any number of equidistant points or azimuths—or, to speak more exactly, the mean of the northern components of these forces $= 1$.

The diminution of force observed, therefore, cannot arise from the effect of permanent magnetism, but that it arises from the horizontal induction in soft iron can be readily explained, and is easy of experimental proof. If we place a compass in the centre of a circular vessel, or over a circular plate of purely soft iron, no deviation will be produced, but the directive force of the needle will be diminished: this arises from the magnetism induced in the circular vessel, or plate, by the earth's magnetism acting in a direction antagonistic to that of the earth's force.*

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* Hence the necessity of compasses of the best workmanship and strong directive force.

How is the directive force determined on board ship on any given course?

A. There are several ways, but the most simple and convenient in ordinary practice is by observing the time of a certain number of vibrations of a small needle at the place of the compass; and also on shore†; the direction of the ship's head being noted at the time of observation on board, and the deviation for that direction known. Now the proportion of the earth's horizontal force between any two places is known to be inversely as the square of the number of seconds occupied by the same number of vibrations. If, therefore, the time of making (say) 10 vibrations on shore is found to be 20 seconds, and the time of making 10 vibrations at the place of the compass on board 28 seconds, then the horizontal force at the compass—*i. e.*, the horizontal force of earth and ship combined—is $(\frac{20}{28})^2 = \frac{400}{784}$, or 0·51, the horizontal force on shore being represented by 1. Similarly, if the time of making 10 vibrations at the compass is 16 seconds, the horizontal force is $(\frac{20}{16})^2 = \frac{400}{256}$, or 1·5, the horizontal force on shore being represented by 1. In the first example the ship's force is acting *against*, and in the second example *with*, the earth's force. (See pp. 35, 36, 38.)

The horizontal force thus found at the compass is that of the earth, that of the ship's permanent magnetism, and that induced in the soft iron combined—directed, it must be remembered, in the line in which the needle points. In order, therefore, to find the amount of force in the direction of the magnetic north, the observed horizontal force must be multiplied by the cosine of the deviation.

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* A similar effect, but of increased amount, is produced when the compass is completely enclosed in an iron vessel, as a bomb-shell. The effect increases rapidly with the thickness of the shell, and where it bears a sensible proportion to the diameter of the shell—say one-tenth—the destruction, or rather counteraction of directive force is nearly total. Hence we may easily see how a compass placed above an iron deck, and still more between iron decks, appears to lose a great part of its directive force.

† A convenient and very efficient needle for observations of horizontal force on board ship will be found of the following size and form:—Length 2¾ inches, width one-third of an inch at the central part, flat, pointed at the ends, and generally of a double convex form; it should be as thin as can be made consistent with strength and rigidity. Such a needle, on a fine pivot of its own, will, in an arc not exceeding 45°, at its commencement, make 10 vibrations in 19 or 20 seconds on shore, and will continue its vibrations to the extent of 80 or 100. The pivot of this needle should fit into the pivot socket of the Standard compass, care should be taken for its preservation, and it should not be changed at any time for the ordinary ship's pivots.

The mean value of the force thus found, for the entire revolution of the ship's head (usually less than 1. in iron ships) is known as the co-efficient λ* (*lambda*).

λ does not change with change of geographical position.†

How is λ determined?

A. If, in the entire revolution of the ship's head, we observe the horizontal force on four or more equidistant azimuths (*i. e.*, true or magnetic, *not* compass), λ can be obtained, from the mean of the several values of $\frac{H'}{H}\cos\delta$ (see foot-note); λ is also the mean of the forces at N. and S., or the value of the force at any cardinal point if the semicircular deviation be mechanically corrected.

If we cannot obtain observations of force which would give λ in the ways described, it can readily be obtained on any one single azimuth, if the co-efficients $\mathfrak{B}$, $\mathfrak{C}$, $\mathfrak{D}$, are known in addition to the horizontal force of the ship and earth, and to the amount of deviation for that azimuth.

Why are the co-efficients $\mathfrak{B}$, $\mathfrak{C}$, $\mathfrak{D}$, then required?

A. In order to ascertain how much the earth's horizontal force—considered as 1—is affected by the ship's horizontal force as represented by those co-efficients: this will be rendered clear by a consideration of the following examples, illustrated by a graphic method.

The examples are selected from observations made in H.M.S. Achilles. It will be seen that, with the ship's head in the first and fourth quadrants, the quadrantal and semicircular deviations combine to increase the earth's force; in the second and third quadrants they combine to decrease the earth's force.

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* In other words, λ represents the proportion of the mean horizontal force northward on board, to the horizontal force on shore, and is the mean value of $\frac{H'}{H}\cos\delta$, where

H is the horizontal force of the earth
H′ „ „ „ earth and ship
δ the deviation of the compass
$\frac{H'}{H}=\frac{T^2}{T'^2}$
T = time of a certain number of vibrations on shore
T′ = „ „ „ on board.

† There is reason to believe that λ is affected by temperature;—decreasing by heat—but by quantities not affecting the navigator.

Describe, first, the graphic method for determining λ (*lambda*).

A. It is as follows (see figure 21):—

1. Draw a vertical line S N—supposed to lie north and south magnetic, upper part north—of any length conveniently divisible into 100 equal parts; this length to represent the earth's horizontal force $= 1 \cdot 0$, each division being therefore $\cdot 01$.

2. With N as centre, describe a circle whose radius equals $\mathfrak{D}$.

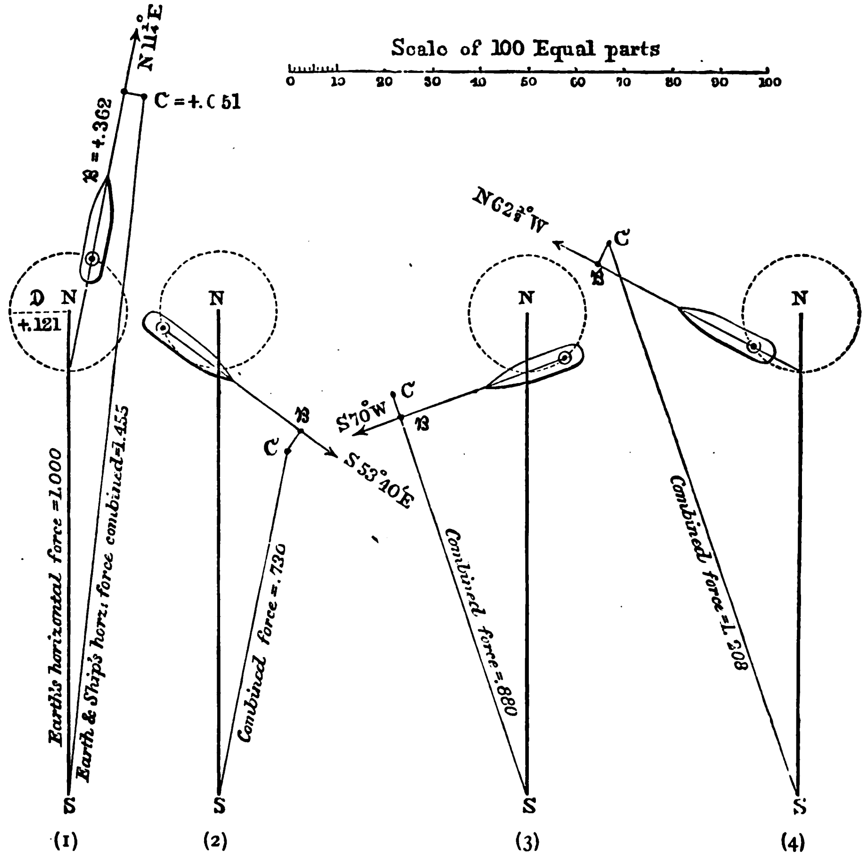
3. Through the part of the $\mathfrak{D}$ circle, cutting the vertical line, draw a line parallel to the ship's keel (or the magnetic azimuth of ship's head) intersecting the circle a second time in a point which will represent the position of the ship's Standard compass. If the ship's head is in the northern semicircle, this line will represent the direction of the ship's head; if the ship's head is in the southern semicircle, the direction of the ship's stern.

4. For the sake of clearness, draw round the position of the Standard compass the figure of a ship with her head directed in the direction of the ship's head.

5. From the position of the Standard compass, and from the same scale of equal parts, lay off $\mathfrak{B}$ ahead or astern of the Standard compass, according as $\mathfrak{B}$ is + or —. From $\mathfrak{B}$ erect a perpendicular, and on it lay off $\mathfrak{C}$ (from same scale of equal parts) to starboard or port of $\mathfrak{B}$ according as $\mathfrak{C}$ is + or —.

6. Then the length of the line S $\mathfrak{C}$ represents the whole horizontal directive force on the needle divided by λ; and hence λ is equal to the horizontal force of the needle obtained by the formula $\frac{T^2}{T'^2}$ divided by the length S $\mathfrak{C}$.

Fig. 21.



Example of graphic method, from four sets of horizontal force observations made in H.M.S. Achilles, Sheerness, October, 1864.

Exact co-efficients. $\mathfrak{B} = + \cdot 362$ $\mathfrak{C} = + \cdot 051$ $\mathfrak{D} = + \cdot 121$ (See p. 61.)	Ship's head by Standard compass, or ζ'	Deviation, or δ	Ship's head corresponding magnetic, or ζ	Time of 10 vibrations, on board, or T′	Time of 10 vibrations on shore, or T
				Seconds.	
(1).—	N. 6° 0′ E.	5° 15′ E.	N. 11° 15′ E.	19·16	Seconds. 20·60
(2).—	S. 65 30 E.	11 50 E.	S. 53 40 E.	26·83	
(3).—	S. 87 40 W.	17 40 W.	S. 70 0 W.	24·38	
(4).—	N. 43 0 W.	19 30 W.	N. 62 30 W.	20·80	

(*Continued.*)

(1)	(2)	(3)	(4)
$\frac{T^2}{T'^2} = \frac{424{\cdot}4}{367{\cdot}1}$	$\frac{T^2}{T'^2} = \frac{424{\cdot}4}{719{\cdot}8}$	$\frac{T^2}{T'^2} = \frac{424{\cdot}4}{594{\cdot}4}$	$\frac{T^2}{T'^2} = \frac{424{\cdot}4}{432{\cdot}6}$
or	or	or	or
$\frac{H'}{H} = 1{\cdot}156$	$\frac{H'}{H} = {\cdot}590$	$\frac{H'}{H} = {\cdot}714$	$\frac{H'}{H} = {\cdot}981$
$\lambda = \frac{\frac{H'}{H}}{S\ C}$	$\lambda = \frac{{\cdot}590}{{\cdot}730}$	$\lambda = \frac{{\cdot}714}{{\cdot}880}$	$\lambda = \frac{{\cdot}981}{1{\cdot}208}$
$= \frac{1{\cdot}156}{1{\cdot}455}$	$= {\cdot}807$	$= {\cdot}811$	$= {\cdot}812$
$= {\cdot}794$			

Mean value of λ by graphic method from four sets of observations . . . . = **·806**

Now give the formula for obtaining λ, as also an example of the method of working it.

A. The formula corresponding to the geometrical solution just given is as follows :—

$$\lambda = \frac{H'}{H} \times \frac{\cos \delta}{1 + \mathfrak{B} \cos \zeta - \mathfrak{C} \sin \zeta + \mathfrak{D} \cos 2\zeta}$$

Taking the example from the same four observations made in H.M.S. Achilles, we have for the computation of λ from the above formula*,

---

* In these and similar calculations, ζ and ζ' (or the azimuth of ship's head magnetic and by compass) is considered as increasing from 0 at N. to 90° at E., 180° at S., 270° at W., and 360°, or 0 again at N. It is therefore necessary to be acquainted with the practice of finding the natural sines and cosines of arcs up to 360°, and giving them their proper signs. As an aid it may be remembered

That an angle may be subtracted from 180° or 360°;
or,
180° or 360° may be subtracted from an angle
} without altering the numerical value of its sine or cosine.

That the sine of an angle in the East semicircle is +
„ „ „ West „ „ —
cosine „ „ North „ „ +
„ „ „ South „ „ —
tangent „ N.E. & S.W. quadrants +
„ „ „ S.E. & N.W. —
sine of a negative angle less than 90° is negative.
cosine „ „ „ 90° is positive.

	T'	T	T'^2	T^2	$\frac{T^2}{T'^2}$ or $\frac{H'}{H}$	δ	$\cos\delta$	ζ	$\cos\zeta$	$\sin\zeta$	2ζ	$\cos 2\zeta$
	Secs.	Secs.										
(1)	19.16	20.60	367.1	424.4	1.156	+ 5° 15′	.996	11° 15′	+.981	+.195	22° 30′	+.924
(2)	26.83	”	719.8	”	.590	+ 11 50	.979	126 20	—.592	+.805	252 40	—.298
(3)	24.38	”	594.4	”	.714	— 17 40	.953	250 0	—.342	—.940	500 0	—.766
(4)	20.80	”	432.6	”	.981	— 19 30	.943	297 30	+.462	—.887	595 0	—.573

The exact co-efficients (see page 61) $\mathfrak{B} = +{\cdot}362$ $\mathfrak{C} = +{\cdot}051$, $\mathfrak{D} = +{\cdot}121$.

$$(1)\quad \lambda = 1{\cdot}156 \times \frac{{\cdot}996}{1 + ({\cdot}362 \times {\cdot}981) - ({\cdot}051 \times {\cdot}195) + ({\cdot}121 \times {\cdot}924)}$$

$$= 1{\cdot}156 \times \frac{{\cdot}996}{1{\cdot}457} = 1{\cdot}156 \times {\cdot}683$$

$$= \mathbf{{\cdot}790}$$

$$(2)\quad \lambda = {\cdot}590 \times \frac{{\cdot}979}{1 + ({\cdot}362 \times -{\cdot}592) - ({\cdot}051 \times {\cdot}805) + ({\cdot}121 \times -{\cdot}298)}$$

$$= {\cdot}590 \times \frac{{\cdot}979}{{\cdot}709} = {\cdot}590 \times 1{\cdot}382$$

$$= \mathbf{{\cdot}815}$$

$$(3)\quad \lambda = {\cdot}714 \times \frac{{\cdot}953}{1 + ({\cdot}362 \times -{\cdot}342) - ({\cdot}051 \times -{\cdot}940) + ({\cdot}121 \times -{\cdot}766)}$$

$$= {\cdot}714 \times \frac{{\cdot}953}{{\cdot}830} = {\cdot}714 \times 1{\cdot}147$$

$$= \mathbf{{\cdot}820}$$

$$(4)\quad \lambda = {\cdot}981 \times \frac{{\cdot}943}{1 + (362 \times {\cdot}462) - ({\cdot}051 \times -{\cdot}887) + {\cdot}121 \times -{\cdot}573}$$

$$= {\cdot}981 \times \frac{{\cdot}943}{1{\cdot}143} = {\cdot}981 \times {\cdot}825$$

$$= \mathbf{{\cdot}809}$$

Mean value of λ by calculation from four sets of observations = **·809.***

On the connection between λ and $\mathfrak{D}$.

Then, as λ is proved to result from horizontal induction in soft iron, it must be directly connected with the co-efficient $\mathfrak{D}$—is this so ?

A. It is intimately connected; for in the imaginary rods of soft iron we have described in Section IV. p. 40, known as *a* and *e*, when either rod passes through the compass it *diminishes* the directive force of the needle, as on the ship revolving in azimuth it acts by *pushing* the nearer end and pulling the further end of the needle. When the rod is wholly on one side of the compass it *increases* the directive force as it acts by *pulling* the nearer and pushing the further end of the needle.

When the value of λ is known in addition to that of $\mathfrak{D}$, we can find from which arrangement of imaginary rods $\mathfrak{D}$ arises.

*** The difference between these values and those derived from the graphic construction are due to the inevitable errors of all graphic constructions.**

What appears from these investigations to be the chief cause of $\mathfrak{D}$?

A. In almost all iron ships the positive value of $\mathfrak{D}$ arises from the transverse iron continued from side to side—such as beams, decks, bulkheads, and the ship's bottom, conducted as it were upwards by the iron sides, producing a large $-e$ and overcoming the force of the fore and aft iron, which gives a sometimes $+$ and sometimes $-$, but when $-$ always less than e.*

How are these relations of λ and $\mathfrak{D}$ simply expressed in an algebraical form?

A. As λ equals half the sum of the forces produced by the rods a and e added to the earth's horizontal force, it may be thus expressed:—

$$\lambda = 1 + \frac{a+e}{2}.$$

As $\mathfrak{D}$ equals half the difference of the forces produced by the rods a and e divided by λ, it may be thus expressed:

$$\mathfrak{D} = \frac{a-e}{2\lambda},$$

from whence it follows that the parts of $\mathfrak{D}$ arising from fore and aft induction

$$= \frac{a}{2\lambda} = \frac{\mathfrak{D} - \left(\frac{1}{\lambda} - 1\right)}{2},$$

and from transverse induction,

$$= \frac{-e}{2\lambda} = \frac{\mathfrak{D} + \left(\frac{1}{\lambda} - 1\right)}{2}.$$

To obtain the values of a and e, we also have

$$\begin{aligned} 1 + a &= \lambda(1 + \mathfrak{D}) \\ 1 + e &= \lambda(1 - \mathfrak{D}) \end{aligned}$$

or

$$\begin{aligned} a &= \lambda\mathfrak{D} - (1 - \lambda) \\ e &= -\lambda\mathfrak{D} - (1 - \lambda) \end{aligned}$$

Give an example how the values of a and e and the two parts of $\mathfrak{D}$ are derived from this formula.

---

* The armour-plating of a ship of war, if continued from end to end, will give a large $-a$, a small $-e$, and therefore tends to diminish the quadrantal deviation; its principal prejudicial effect is to diminish the directive force.

If the armour-plating is not continued from end to end, but stops short near the position of the Standard compass, and there is then a transverse armour bulk-head, then there is a small $-a$, a large $-e$, producing a large quadrantal deviation and a small or diminished directive force.

Example.

A. H.M.S. Achilles,—required the values of *a*, *e*, and the two parts of $\mathfrak{D}$; λ having been determined $= \cdot 810$, $= + \cdot 121$.

$$a = \lambda \mathfrak{D} - (1 - \lambda)$$
$$= (\cdot 810 \times \cdot 121) \quad - \cdot 190 \quad = \quad - \cdot 092$$

$$e = - \lambda \mathfrak{D} - (1 - \lambda)$$
$$= (- \cdot 810 \times \cdot 121) - \cdot 190 \quad = \quad - \cdot 288$$

Part of $\mathfrak{D}$ from fore and aft induction $= \dfrac{\mathfrak{D} - \left(\frac{1}{\lambda} - 1\right)}{2}$

$$= \tfrac{1}{2} (\cdot 121 - \cdot 235)$$
$$= - \cdot 057 = \quad - 3^\circ \; 16'.$$

" " transverse indution $= \dfrac{\mathfrak{D} + \left(\frac{1}{\lambda} - 1\right)}{2}$

$$= \tfrac{1}{2} (\cdot 121 + \cdot 235)$$
$$= + \cdot 178 = \quad + 10^\circ \; 15'.$$

That is, in the Achilles, soft iron in a fore and aft direction produces a *negative* $\mathfrak{D}$ of 3° 16′; whilst that in a transverse direction produces a *positive* $\mathfrak{D}$ of 10° 15′—in other words, the forces may be represented by two soft iron rods extending through the compass, the transverse rod being three times as powerful as the fore and aft one, the latter, *a* being represented by the value — ·092; the former, — *e* by the value ·288.

SECTION VIII.

On the determination of $\mathfrak{B}$ and $\mathfrak{C}$, from observations made with the ship's head on one azimuth; for example, on the stocks, in dock, or elsewhere.

Are there any means of determining the co-efficients without actually swinging the ship?

A. There are means of so determining them, and to a very considerable degree of approximation. The co-efficients, when the ship is upright, may be considered as six in number, *viz.*, taking the most important first,

$$\mathfrak{B},\ \mathfrak{C},\ \mathfrak{D},\ \lambda,\ \mathfrak{A},\ \mathfrak{E}:$$

of these $\mathfrak{A}$ and $\mathfrak{E}$ are so small, when the compass is in the middle line of the ship, that they may be neglected. Besides this, they do not alter, and therefore when their values are once ascertained by swinging the ship, they may be used in cases when she cannot be swung.

So when $\mathfrak{D}$ and λ are once ascertained, their values may be used in cases when the ship cannot be swung. Or, if not known, they are so nearly the same in similar positions in similar ships, that, after sufficient experience has been obtained, or even by rule, a close approximation may be made to them by estimate.

This leaves only $\mathfrak{B}$ and $\mathfrak{C}$ as really unknown quantities; and if for one magnetic azimuth of the ship (ζ) we know the corresponding compass azimuth (ζ'), and if for one value of the force on shore (H) we know the corresponding value of the force on board (H′), on the same azimuth, we may determine $\mathfrak{B}$ and $\mathfrak{C}$ by the formulæ

$$\mathfrak{B} = +\frac{1}{\lambda}\cdot\frac{H'}{H}\cos\zeta' - (1+\mathfrak{D})\cos\zeta$$

$$\mathfrak{C} = -\frac{1}{\lambda}\cdot\frac{H'}{H}\sin\zeta' + (1-\mathfrak{D})\sin\zeta$$

in which it will be seen that all the quantities on the right-hand side of the equations are known, or may be determined by observations made with the ship's head on one magnetic azimuth, ζ.

What are the most probable values of 𝔇 and λ in the usual position of the Standard compass in ships of different classes?

ANSWER.

	Standard Compass.			Steering Compass.		
	D	𝔇	λ	D	𝔇	λ
In iron-built ships with iron decks, completely armour plated . .	+ 5¾°	.100	.850	7°	.122	.800
In iron-built ships, partially armour plated, and with tranverse armour*	+ 7	.122	.800	10	.174	.775
Wood-built ships (iron deck), armour plated	+ 3	.052	.910	2¾	.048	.900
Iron-built steam troop and store ships	+ 5	.087	.875	6½	.113	.850
,, sailing merchant ships .	+ 4½	.078	.850	Uncertain.		
Composite wood and iron-built ships	+ 4	.070	.940			
Wood-built paddle steam-vessels .	+ 1½	.026	1.000			
,, screw ,,	+ ½ − ¼	.005	—			

Are there any, and what, advantages in being able to determine the co-efficients 𝔅 and ℭ without actually swinging the ship?

A. There are. First, we may then select a favourable position for the Standard compass while the ship is building: we can obtain a complete history of the ship's magnetism, and its changes, on the stocks and in dock, and when moored head and stern; and, further—and this is perhaps the greatest practical advantage—we can, without going through the laborious and tedious operation of swinging a large ship, obtain the co-efficients with a sufficient degree of approximation to enable us to reduce the semicircular deviation by mechanical correction to an amount which can be easily and safely corrected by tables of deviation.†

The ship being on the stocks or in dock, describe in detail the observations and calculations to be made to determine 𝔅 and ℭ?

A. First: Place a compass in the exact position intended for the Standard compass, and observe by it the compass azimuth of the ship's head. Then obtain ζ, the magnetic azimuth of the ship's head, by an

---

[*] On the main deck of these ships, D is increased to 14°, and λ reduced to .750.

[†] Merchant ships are at present often sent to sea without any fresh swinging, notwithstanding that iron may have been taken on board as cargo, or that the ship may have lain for a long time in one position. In such a case, the navigator, competent to make the requisite observations and calculations, can easily discover whether such changes have taken place as to make a fresh swinging necessary.

azimuth of the sun, or the bearing of a distant object whose magnetic azimuth is known, or by observing with an azimuth compass on shore in the line of the ship's masts, at a sufficient distance ahead or astern, to avoid local error.

Second: At the *exact* position of the Standard compass, observe T′, the time of ten vibrations of the horizontal needle described in foot-note, p. 68, T the time of ten vibrations of the same needle on shore, and compute

$$\frac{H'}{H} = \frac{T^2}{T'^2}$$

Then compute 𝔅 and ℭ from the formulæ.*

Can 𝔅 and ℭ be obtained without going through this calculation?

A. Yes; by a graphic method, easily and rapidly performed when it has once become familiar.

The following is the process:—

1. From S draw S N = 1, upwards, and of any convenient length, easily divisible into 100 parts: the direction S N representing that of the magnetic north.
2. With centre N, and radius 𝔇, describe a circle cutting S N in D.
3. Through D draw D 𝔅 in the direction of the ship's keel, and which will cut the circle in a second point ⊙.
4. For the sake of clearness, draw round ⊙ an outline sketch of a ship, so that ⊙ may represent the position of the Standard compass, and so that the head of the outline ship may be directed in the same direction as the ship's head.
5. From S draw S C in the direction of the compass North, or such that N S C is the deviation observed, and let $SC = \frac{1}{\lambda} \cdot \frac{H'}{H} = \frac{1}{\lambda} \cdot \frac{T^2}{T'^2}$.

   (The step here taken of multiplying $\frac{H'}{H}$ by $\frac{1}{\lambda}$ must not be forgotten.)
6. From C let fall a perpendicular C 𝔅 on 𝔇 𝔅.

   Then ⊙ 𝔅 = 𝔅

   𝔅 C = ℭ

   𝔅 being + or — according as it lies ahead or astern of ⊙ on the outline ship;

   ℭ being + or — according as it lies to starboard or to port of ⊙ on the outline ship.

---

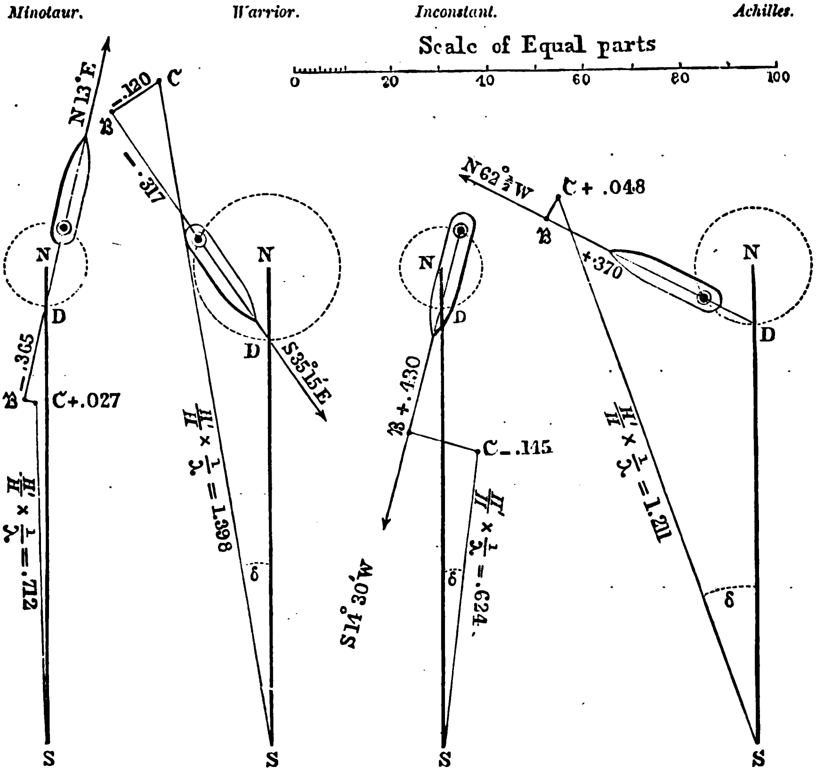
* It will be remembered that with 𝔅, ℭ, 𝔇 known, a table of deviations can be readily formed. (See pages 63—66.)

Graphic method for determining 𝔅 and ℭ, with ship's head in one azimuth—𝔇 and λ being known or assumed.

Examples of four iron ships in dock, with their heads in different directions.

		Minotaur.	*Warrior.*	*Inconstant.*	*Achilles.*
Assumed or known	$\mathfrak{D}$ =	+.081	+.148	+.085	+.121
	λ =	.880	.875	.890	.810
Ship's head by compass, or	ζ' =	N. 14° 30′ E.	S. 26° 15′ E.	S. 7° 40′ W.	N. 43° 0′ W.
,, magnetic, or	ζ =	N. 13 0 E.	S. 35 15 E.	S. 14 30 W.	N. 62 30 W.
Deviation $(\zeta' - \zeta)$ or	δ =	1 30 W.	9 0 W.	6 50 E.	19 30 W.
Time of ten vibrations in ship,	T′ =	28.70 sec.	22.60 sec.	30.58 sec.	20.80 sec.
,, ,, on shore,	T =	22.73 ,,	25.0 ,,	22.80 ,,	20.60 ,,
	$\frac{T^2}{T'^2}$ =	$\frac{516.6}{823.7}$	$\frac{625.0}{510.8}$	$\frac{510.8}{935.1}$	$\frac{424.4}{432.6}$
Or,	$\frac{H'}{H}$ =	.627	1.223	.556	.981
	$\frac{H'}{H} \times \frac{1}{\lambda}$ =	.627×1.136	1.223×1.143	.556×1.123	.981×1.235
	=	.712	1.398	.624	1.211

Figure 22.


Minotaur.
Warrior.
Inconstant.
Achilles.
Scale of Equal parts
0
20
40
60
80
100
N13°E
—.120
C
𝔅
—.317
N
D
—.365
𝔅
C+.027
$\frac{H'}{H} \times \frac{1}{\lambda} = .712$
N
D
S35°15′E
$\frac{H'}{H} \times \frac{1}{\lambda} = 1.398$
δ
S
S
N62°½W
C+.048
𝔅
+.370
N
D
N
D
𝔅+.430
C—.145
S14°30′W
$\frac{H'}{H} \times \frac{1}{\lambda} = .624$
δ
S
$\frac{H'}{H} \times \frac{1}{\lambda} = 1.211$
δ
S

𝔅 = — .365	𝔅 = — .317	𝔅 = + .430	𝔅 = + .370
ℭ = + .027	ℭ = — .120	ℭ = — .145	ℭ = + .048

The formulæ corresponding to the geometrical solution being as follows :—

$$\mathfrak{B} = + \frac{1}{\lambda} \times \frac{H'}{H} \cos \zeta' - (1 + \mathfrak{D}) \cos \zeta$$

$$\mathfrak{C} = - \frac{1}{\lambda} \times \frac{H'}{H} \sin \zeta' + (1 - \mathfrak{D}) \sin \zeta$$

Examples of computation. The four iron ships used as in graphic method.

	$\mathfrak{D}$	$\frac{1}{\lambda}$	ζ'	δ	ζ	$\frac{H'}{H}$	$\frac{1}{\lambda} \times \frac{H'}{H}$	$\cos \zeta'$	$\sin \zeta'$	$\cos \zeta$	$\sin \zeta$
			° ′	° ′	° ′						
Minotaur .	+.081	1.136	14 30	− 1 30	13 0	.627	.712	+.968	+.250	+.974	+.225
Warrior .	+.148	1.143	153 45	− 9 0	144 45	1.223	1.398	−.897	+.442	−.817	+.577
Inconstant.	+.085	1.123	187 40	+ 6 50	194 30	556	.624	−.991	−.133	−.968	−.250
Achilles .	+.121	1.235	317 0	−19 30	297 30	.981	1.211	+.731	−.682	+.462	−.887

Minotaur . .

$$\begin{aligned}\mathfrak{B} &= (1.136 \times .627) \times .968 - (1.081 \times .974) \\ &= .712 \times .968 - 1.053 \\ &= .689 - 1.053 \\ &= -\mathbf{.364.}\end{aligned}$$

$$\begin{aligned}\mathfrak{C} &= - .712 \times .250 + .919 \times .225 \\ &= - .178 + .207 \\ &= + \mathbf{.029.}\end{aligned}$$

Warrior . .

$$\begin{aligned}\mathfrak{B} &= (1.143 \times 1.223) \times -.897 - (1.148 \times -.817) \\ &= 1.398 \times -.897 + .938 \\ &= - 1.254 + .938 \\ &= + \mathbf{.316.}\end{aligned}$$

$$\begin{aligned}\mathfrak{C} &= - 1.398 \times .442 + .852 \times .577 \\ &= - .618 + .492 \\ &= - \mathbf{.126.}\end{aligned}$$

Inconstant . .

$$\begin{aligned}\mathfrak{B} &= (1.123 \times .566) \times -.991 - (1.085 \times -.968) \\ &= .624 \times -.991 + 1.050 \\ &= - .618 + 1.050 \\ &= + \mathbf{.432.}\end{aligned}$$

$$\begin{aligned}\mathfrak{C} &= - .624 \times - .133 + (.915 \times - .250) \\ &= + .083 + (- .229) \\ &= - \mathbf{.146.}\end{aligned}$$

Achilles . .

$$\begin{aligned}\mathfrak{B} &= (1.235 \times .981) \times .731 - (1.121 \times .462) \\ &= 1.211 \times .731 - .518 \\ &= .885 - .518 \\ &= + \mathbf{.367.}\end{aligned}$$

$$\begin{aligned}\mathfrak{C} &= - 1.211 \times - .682 + (.879 \times - .887) \\ &= + .826 - .779 \\ &= + \mathbf{.047.}\end{aligned}$$

Note.—The differences between these results and those obtained by the graphic method, depend, of course, on the inevitable errors of all graphic methods.

SECTION IX.

On the changes of the deviations of the Compass that take place after launching: as arising from the lapse of time, and from changes of geographical position.

We have seen that a definite magnetic character is impressed on every ship while building: what do we know of the subsequent states of the ship's magnetism when the ship is launched?

A. Experience has clearly established that the definite magnetic character thus impressed (see fig. 3, p. 34) is never afterwards entirely lost, but nevertheless that after launching, the magnetic state of an iron ship is for some time very unstable*: also, that after a few months' active service, or even of swinging at moorings, the changes gradually become smaller, and that, in a year or two, the magnetism of the ship acquires a very permanent character, and more especially so if employed in the hemisphere in which she was built.

How are these changes and the subsequent permanency explained?

A. We have seen that the original semicircular deviation depends in great part on the direction of the ship's head in building, and that it consists chiefly in an attraction of the N. end of the needle to the part of the ship which was south in building. This principal part is caused by the sub-permanent† magnetism induced in the ship when building by the earth's *horizontal* force.

But a further part of the semicircular deviation is independent of the direction of the ship in building; it consists in an attraction of the N. end of the needle to the bow or stern, and is the effect of the sub-permanent, combined with the transient magnetism induced in the ship by the earth's *vertical* force. In the usual place of the Standard compass, this part is small, and, in the northern hemisphere, is usually an attraction towards the bow; but if the compass is placed nearly in front of the upper part of a large vertical mass of iron, as the rudder or stern-post, it may be towards the stern.

---

* Hence the necessity of constantly verifying the deviation tables in a newly-built iron ship.

† This term was originally used by the Astronomer Royal to distinguish the difference in character of the permanent magnetism of an iron ship from that of the magnetism of a magnetised steel bar, implying that the former, though changing slowly, still does change, and has not the same degree of permanence as the magnet bar. As employed in the text, it is therefore to be considered as permanent magnetism in this restricted sense. (See Section IV., p. 32–3.)

It is the first, or principal part of the semicircular deviation that diminishes rapidly after the ship has been launched, and that in the course of time—a year or two—if the ship has been swinging on all azimuths, attains its fixed and permanent character. The secondly described part changes little, if at all, so long as the ship remains in the same magnetic latitude.

Has that part of the sub-permanent and transient magnetism induced by the earth's vertical force any effect in producing ℭ?

A. No; at least if the iron as regards position and quality is symmetrically placed on each side of the midship line. In that case ℭ can only arise from sub-permanent magnetism induced in the process of building by the transverse horizontal force of the earth. ℭ also, therefore, may be expected to diminish after launching until the time arrives beyond which sensible changes do not proceed.

It appears then that 𝔅 is the great changing quantity?

A. This in general is so, as will be seen when speaking of changes due to changes of geographical position. It must however be observed that in a compass favourably placed with reference to vertical iron, by there being an equal distribution on either side before and abaft, the original value as well as the changes, even on changes of magnetic latitude, arising from sub-permanent and transient magnetism induced by the vertical force, would be very small, while if unfavourably placed with regard to vertical iron, such as being near the rudder-head, or stern-post, there would be assuredly very large changes on changes of magnetic latitude.

It is from the combination of these several causes that the determination of the proportion of the parts of 𝔅 which severally arise from vertical induction in soft iron, and the sub-permanent magnetism of hard iron, and the estimate of the proportion of change on a change of latitude, becomes a matter of difficulty.

Can you give an illustrative example of the changes in 𝔅 and ℭ in a newly launched ship and afterwards?

A. The Achilles affords a good illustration.

Originally built and plated in dock at Chatham, with head S. 52° E.

(mag.), she is floated out on the 23rd December, 1863, moved into the river Medway, and secured with head nearly in the same direction (S. 62° E.) for the purpose of taking in machinery, iron masts, and to equip for sea. Three months afterwards, in March 1864, the ship makes a short trial trip in the river, and then resumes her former moorings—but placed in an exactly opposite direction, or N. 62° W.: seven months afterwards, or on October 12th, being completed for sea, the ship steams to Sheerness and is swung, commencing thus her sea service.

The following, arranged in order of time, shows the changes in the several co-efficients :—

			𝔅.	ℭ.
1863.	Dec. 23.	Chatham, in dock, head S. 52° E.	+ ·464	+ ·323
1864.	Sept. 26.	„ moored „ N. 62 W.	+ ·377	+ ·037
„	Oct. 12.	„ „ „ S. 55 E.	+ ·355	+ ·062
„	Oct. 13.	Sheerness, completely swung	+ ·362	+ ·051
„	Dec.	Plymouth „	+ ·361	+ ·123
1865.	April	Portland „	+ ·322	+ ·191
„	June	Plymouth „	+ ·288	+ ·124
1866.	Aug.	„ „	+ ·308	+ ·138
1867.	April	„ „	+ ·309	+ ·146
1868.	April	„ „	+ ·314	+ ·132
1869.	June	„ „	+ ·305	+ ·127

We see here a large + value originally given to ℭ by the ship being built, armour-plated, fitted with machinery, and in part equipped with her starboard side to the south; the ℭ then nearly disappearing from the ship lying with her port side to the south for seven months. In the first six months of sea service, with the ship's head on all azimuths, ℭ gradually increases in value, the ship assuming the distinctive character due to the original direction in building. In April, 1865, ℭ has reached its maximum value; all this time 𝔅 has gradually diminished till, in another two months, or eight months after commencing sea-service, 𝔅 and ℭ attain their settled values, at which they have, with singularly small variations remained till the present time.* This will be clearly seen by the direction and amount of the ship's horizontal force $\left(\tan^{-1}\frac{\mathfrak{C}}{\mathfrak{B}} \text{ and } \sqrt{\mathfrak{B}^2+\mathfrak{C}^2}\right)$ at two distinct periods :

---

* This permanence of character is found in all the ships of the Royal Navy, not withstanding the constant tremors they undergo by the firing and exercising heavy guns, and when under steam at high speed; as also the occasional jars in docking.

It has been asserted that the firing heavy guns affects the magnetism of a ship;—there appears to be no grounds for this assumption. In the exceptional cases of a compass being placed on an iron bridge or platform near a turret-gun, as is necessitated sometimes in the smaller class of turret ships, such detached structure may be affected by concussion, apart from the body of the ship; the latter, however obeys the law of change as stated in the text.

June, 1865 157° ·314,
June, 1869 $157\frac{1}{2}$ ·330.

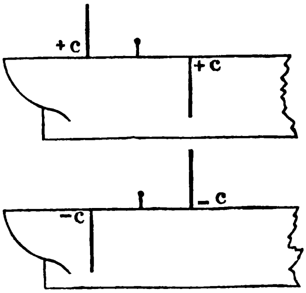
In general practice, what caution may we deduce from these changes in $\mathfrak{C}$?

A. That $\mathfrak{C}$ may be expected to change if the ship be kept long in dock nearly in an east and west direction; if head easterly, to increase $+\mathfrak{C}$ and diminish $-\mathfrak{C}$; if head westerly to diminish $+\mathfrak{C}$ and increase $-\mathfrak{C}$. Similarly if on a voyage when long on easterly or westerly courses. Consequently the tendency is, when changing a course which has been long steered, to err in the direction of the old course—so that if an iron ship steers long on a northerly course and then changes it to east, she will go to the north of the new course. This gives ships coming from the south a tendency to approach too near the English coast in running up channel.

Explain the nature of the changes which take place on change of geographical position?

A. As the effect of any disturbing cause of fixed amount in producing deviation is inversely as the directive force of the needle, and as the permanent magnetism of the "hard" iron of the ship is a disturbing cause of this nature; the deviation produced by it is therefore in the *inverse* ratio of the earth's horizontal force, and will so vary on change of geographic position: but the deviation produced by that part in the ship arising from the magnetism induced in the "soft" iron by the *vertical* force of the earth—principally, as we have seen, existing in $\mathfrak{B}$—is proportional to that vertical force, and therefore when the ship changes her geographical position, this part, instead of varying, as the other part does, *inversely* as the horizontal force, varies as the ratio of the earth's vertical force to the horizontal force, or, in other words, as the tangent of the dip.*

Fig. 23.



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* The parts composing $\mathfrak{B}$ are shown in the following equational form. If we consider the transiently induced part as being represented by a soft iron rod *c* acting vertically in front or abaft the compass of the type in the accompanying figures; and P to represent a magnet bar placed in a fore and aft line with its S. pole directed to the compass (+ if before, — if abaft), to represent the permanent part. H the earth's horizontal force and λ the mean directive force of the needle.

$$\mathfrak{B} = \left(c \times \tan \text{dip} + \frac{P}{H}\right) \times \frac{1}{\lambda}.$$

How do charts of the magnetic elements aid the navigator in estimating the probable changes in the deviation of the compass, on the ship's change of geographic position ?

A. The chart exhibiting the *earth's horizontal force** (Plate V.) enables him to see at a glance the change that will ensue in the effect of the permanent magnetism of the ship. As this change is inversely as the earth's horizontal force, the reciprocal of this force is for convenience in that appended to this work, given at the end of each line : the multiplier for converting the permanent semicircular deviation at one place to that at another is then the product of the value of the horizontal force at the first place and of the reciprocal of the horizontal force at the second place.

For example, a ship leaving England for Bombay with her B and C of the respective values of 6° and 2°, arising from permanent magnetism, would find that at the equator B had decreased to 6° × 0·55 = 3° 18′ ; C to 2° × 0·55 = 1° 6′ ; in approaching the Cape of Good Hope that B had then increased to 6° × 0·83 = 5° ; and C to 2° × 0·83 = 1° 40′. From thence to Bombay the decrease in the co-efficients would be gradual, and at the latter part B would equal 6° × 0·45 or 2° 42′ ; and C would equal 2° × 0·45 or 0° 54′.

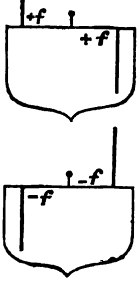
If the ship now leaves for Port Philip, in Australia, the predicted co-efficients for that place would be, B = 2° 42′ × 2·2 (the horizontal force at Bombay) × 0·77 (the reciprocal of the horizontal force at Port Philip) = 4° 24′ ; similarly, C = 0° 54′ × 2·2 × 0·77 = 1° 31′.

The chart (I., Plate IV.) exhibiting the *dip of the needle* enables him to see the changes that will take place in that part of the magnetism of the ship arising from induction in the soft iron by the earth's *vertical force* ;

Similarly $\mathfrak{C}$ may be shown by a soft iron rod f of the accompanying type acting vertically on either side of the compass, and Q to represent a magnet bar placed transversely with its S. pole directed to the compass (+ if on starboard side, — if on port side) ; then

$$\mathfrak{C} = \left(f \times \tan \text{dip} + \frac{Q}{H}\right) \times \frac{1}{\lambda}.$$

Fig. 24.



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* The value of the horizontal force at Greenwich (which may be considered also as the same at the principal naval ports of the country) is assumed in this chart as unity ; this assumption is alone a matter of convenience. In absolute measure the horizontal force at Greenwich is, at the present time (1870), 3·85, which would be the multiplier to the values of the horizontal force given on the chart, if we wished to convert them to the scale of absolute measure adopted by English magneticians, or by 1·77 to that adopted by continental magneticians. (See article "Terrestrial Magnetism," p. 125.)

principally as we have seen existing in B. For convenience, also, in the chart appended to this work, the natural tangent of the dip, which represents the ratio of the changes on change of magnetic latitude has been given in the margin.

If we now conceive that in the example just given, the ship when in England had 3° of + B, arising from vertical induction in soft iron (or $\frac{c}{\lambda}$), in addition to + B of 6° from permanent magnetism; we should find that off the cape of Good Hope this part had changed, according to the change in the natural tangents of the dip of the needle at the two places, *viz.*, + 68° in English Channel — 57° at cape of Good Hope, or as 2·5 to — 1·5 : this 3° of + B will now have changed to — B of 1° 48′, and thus the original + B of 9° formed of the two parts, will at the cape of Good Hope equal 5° — 1° 48′ or + 3° 12′.

In what part of the globe frequented by navigators do we find the changes most seriously affect the compass?

A. Generally over the navigable parts of the globe the earth's horizontal force is greater and the dip of the needle less than what is observed in England; the numerical values of the deviations of the compass in the iron ship (in a properly-placed compass) are therefore generally less during the foreign voyage than at its commencement. There is, however, an exception in the coasts of North America, and especially in the Gulf of St. Lawrence: there the earth's horizontal force rapidly diminishes, and the dip of the needle rapidly increases as we proceed northward; the directive force of the needle is thus diminished to a serious extent, while both elements combine to increase the amount of the deviations in whatever proportions the permanent and induced magnetism may exist, unless they are of opposite signs.

Illustrating this by the former example, where we take the ship in England with 9° of + B, composed of 6° from permanent magnetism and 3° from vertical induction in vertical iron : in the Gulf of St. Lawrence we should have the following change. The 6° from permanent magnetism would increase in the ratio of 1 to 1·5 (the reciprocal of 0·67) or to 9° ; the 3° from vertical induction would increase in the ratio of 2·5 to 4·7 (the natural tangents of the respective dips + 68° and + 78°) or to 5° 40′ : the whole value of B in the Gulf of St. Lawrence would therefore be 14° 40′.

In what proportions do we find in practice the two parts of the semicircular deviation to consist in England?

A. The following are perhaps the nearest values that can be assigned ;—in the usual position of a Standard compass.

In the ordinary iron-built ship, when the compass is free from the influence of particular masses of vertical iron, and when it may be assumed the deviations result from the general magnetism of the ship, (after a few months' active service), from $\frac{1}{4}$th to $\frac{1}{8}$th may be taken for the induced part, and from $\frac{3}{4}$ths to $\frac{7}{8}$ths of the whole magnetism for the permanent part.

In wood-built ships fitted with steam machinery, as well as in those armour-plated, the proportions of the induced and permanent magnetism appear to be nearly equal, and this is probably the effect of these appliances when they form a part of the ordinary iron-built ship, modifying the results that would otherwise obtain from the permanent character of the hull.

As the accuracy of the predictions of the deviations on change of geographical position, is thus seen to depend on our knowledge of the source from which the parts of $\mathfrak{B}$ are derived: how can we determine the numerical values of the two parts distinguished as $\frac{P}{\lambda}$ and $\frac{c}{\lambda}$? (See foot-note, p. 84.)

A. They can be determined in *one* geographical position when observations have been made on two different angles of heel.* Otherwise we require to know $\mathfrak{B}$ as determined in *two* magnetic latitudes in which the dip and horizontal force (H) are known. In this latter case we derive the values $\frac{P}{\lambda}$ and $\frac{c}{\lambda}$ from the two following equations:—

$$\frac{P}{\lambda} + H \tan \text{dip} \frac{c}{\lambda} = \mathfrak{B}\, H$$

$$\frac{P}{\lambda} + H' \tan \text{dip}' \frac{c}{\lambda} = \mathfrak{B}' H'.$$

Example.—H.M.S. Orontes, on the voyage from Plymouth to the Cape of Good Hope and Hong Kong, between October, 1865, and February, 1866, determines at—

Plymouth	$\mathfrak{B}$ =	— ·074
Cape of Good Hope . . .	„ =	— ·136
Hong Kong	„ =	— ·055

The nat: tan: of the dip, and the horizontal force at these places, are—

Plymouth . .	= + 2·46	and	1·00
Cape of Good Hope .	= — 1·43	„	1·17
Hong Kong . .	= + 0·60	„	2·02

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* When a ship is heeled, c is obtained from the changes in $\mathfrak{A}$ and $\mathfrak{E}$, thus : i and i' being the different angles of heel.

$$\frac{c}{\lambda} = \frac{\mathfrak{A}_i - \mathfrak{A}_{i'}}{i - i'} - \frac{\mathfrak{E}_i - \mathfrak{E}_{i'}}{i - i'}.$$

$\frac{P}{\lambda}$ will then $= \mathfrak{B}\, H - \frac{c}{\lambda} H \tan \text{dip}.$

therefore between Plymouth and the Cape of Good Hope,

$$\begin{array}{rl}
(1)\ \frac{P}{\lambda} + 2{\cdot}46\frac{c}{\lambda} & = -{\cdot}074 \\
(2)\ \frac{P}{\lambda} + -1{\cdot}67\frac{c}{\lambda} & = -{\cdot}159 \\
\text{or } 4{\cdot}13\frac{c}{\lambda} & = +{\cdot}085 \\
\therefore \frac{c}{\lambda} & = +\mathbf{{\cdot}021} \\
\text{also } \frac{P}{\lambda} + (2{\cdot}46 \times {\cdot}021) & = -{\cdot}074 \\
\therefore \frac{P}{\lambda} & = -{\cdot}074-({\cdot}051) \\
 & = -\mathbf{{\cdot}125},
\end{array}$$

and between the Cape of Good Hope and Hong Kong,

$$\begin{array}{rl}
(1)\ \frac{P}{\lambda} + -1{\cdot}67\frac{c}{\lambda} & = -{\cdot}159 \\
(2)\ \frac{P}{\lambda} + 1{\cdot}21\frac{c}{\lambda} & = -{\cdot}111 \\
\text{or } 2{\cdot}88\frac{c}{\lambda} & = +{\cdot}048 \\
\therefore \frac{c}{\lambda} & = +\mathbf{{\cdot}017} \\
\text{also } \frac{P}{\lambda} + (1{\cdot}21 \times {\cdot}017) & = -{\cdot}111 \\
\therefore \frac{P}{\lambda} & = -{\cdot}111-({\cdot}021) \\
 & = -\mathbf{{\cdot}132}
\end{array}$$

From whence we see that during the voyage the force of permanent magnetism drawing to the stern of the ship is represented by a mean value of ·128 (sin 7° 22′), and the force arising from induction in vertical iron drawing to the head of the ship is represented by a mean value of ·019 (sin 1° 5′), or the ship has a B of $\frac{-7^\circ\ 22'}{H}$ from hard iron, and + 1° 5′ × tan dip from soft iron.

With these values the amount of B for any geographical position might be confidently predicted; thus, we should have at the Cape of Good Hope,

$$\begin{aligned}
B &= \frac{-7^\circ.36}{1.17} + (1^\circ.04 \times -1.43) \\
&= -6^\circ.29 + -1^\circ.49 \\
&= 7^\circ.78 = 7^\circ\ 47'
\end{aligned}$$

SECTION X.

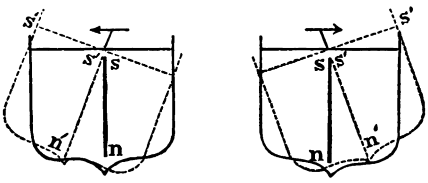
On the Heeling Error.

The deviations hitherto described have been for vessels in an upright position; but as it has been found by experience that when the iron ship heels over, further large deviations are produced, it is necessary that the seaman should be acquainted with the laws of this remarkable compass disturbance; describe therefore the leading features of the heeling error?

A. When an iron ship heels over, forces, which before acted *vertically* and did not disturb the horizontal compass needle,* now act to one side and produce deviation: new forces are also developed by transverse iron which was previously *horizontal*—the beams, for example—becoming inclined, and receiving magnetism by induction from the earth's vertical magnetic force.

In the accompanying figure, the effect of iron beams, and transverse iron generally, in drawing [in north magnetic latitude] the north end of the needle to windward;† and also the effect of vertical soft iron acting *downwards*, further conspiring with the transverse iron in drawing the north end of the needle to windward, is obvious; to which is to be added the vertical action of the permanent magnetism, acting upwards or downwards according to circumstances.

Fig. 25.



The amount of heeling error depends therefore partly on vertical induction in transverse iron, and partly on the vertical force arising from permanent magnetism in the iron of the ship, combined with that arising from vertical induction in vertical soft iron.

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* A simple experiment will illustrate this; for if a bar-magnet is placed vertically under the centre of a compass needle, the latter is not affected in its direction; but if the magnet be moved, however little from the vertical position, a movement of the compass needle follows.

† The upper end of the iron deck beams when inclined—*s' s'* in the northern magnetic latitudes—obviously become S. poles. (See Section IV., p. 31.)

Experience tells us that in some few cases in iron ships, the north end of the needle is drawn to leeward in heeling over; but that, in the majority of cases in England, and in north magnetic latitudes, the north end of the needle is drawn to windward. How is this difference of effect accounted for?

A. By reference to fig. 3, p. 34, it will be seen that the permanent vertical force arising from induction while building in vertical iron may in some cases act *upwards*, in other cases *downwards*. In the ship built head north, for example, there is a strong vertical force acting downwards, from the whole after body of the ship having S. polarity; this would conspire with the vertical induction in transverse iron, in attracting the north end of the needle to the weather side as the ship heels over; but in the ship built head south the vertical force acts *upwards*, from the after body of the ship having N. polarity, and the north end of the needle, as the ship heels over, is repelled by it to the lee side, the vertical force acting in antagonism in this case to the transverse force. The heeling error, therefore, in the ship built head south may be to the *lee* side, from the leeward component of the upward force of the vertical iron exceeding the windward component of the force induced in the transverse iron.

Then, in the ordinary position of the compass on the quarter-deck, we may, if we know the direction in which the ship's head was built, anticipate the direction of the heeling error, and form an approximate estimate of its amount?

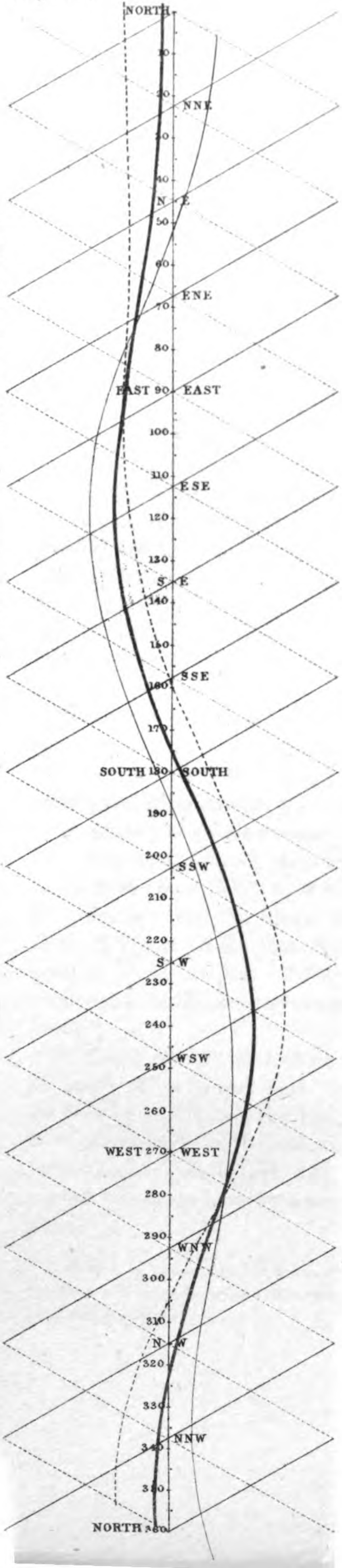
A. Clearly so in most cases; for if we consult fig. 18, p. 50, it will be seen that at the usual place of the compass in ships built with their heads from about S.W. to S.E. by way of north, the upper parts have S. polarity; and in those of this group built with their heads from N.W. to N.E., this S. polarity is strongly developed near the position of the compass. In all these ships the north end of the compass needle will be drawn to windward, and forcibly so in the last-named group.*

In the ships built with their heads from about S.W. to S.E. by way of south, their upper parts near the position of the compass have N. polarity, and hence the heeling error will be to leeward or to windward, accordingly as the vertical force or the force from transverse iron predominates. In either case it will be comparatively small. These several inferences have been verified by direct observation in ships heeled over.

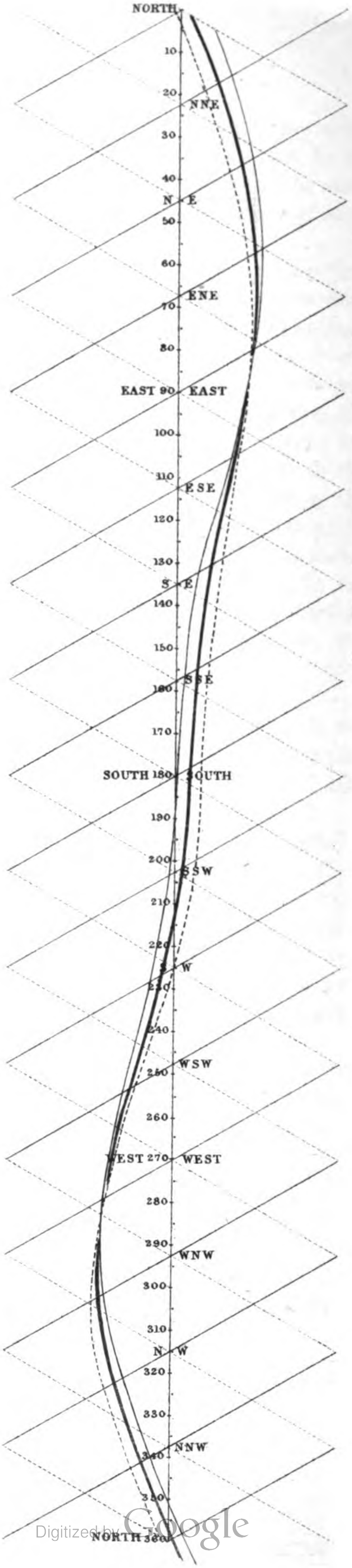
* Hence, in general in the northern hemisphere, an iron ship steering by Standard compass will edge to windward sailing north, and sailing south will edge to leeward. (See also p. 16.)

Plate III.
(to face page 91)

HEELING ERROR CURVES.



H.M.S. Warrior, *Lisbon, Jan: 1863.*
fine line Curve when Heeled 7½° to Port.
deep " " Upright.
broken " " Heeled 7½° to Starboard.



H.M.S. Defence, *Lisbon, Jan: 1863.*
fine line Curve when Heeled 7¼° to Port.
deep " " Upright.
broken " " Heeled 7¼° to Starboard.

How does heeling affect the co-efficients, as determined when the ship is upright?

A. It leaves unaltered those which depend on fore and aft action, *viz.*, B and D; *notably it alters* C, and gives slight values to A and E. Practically, the whole change may be considered to take place in C, and this important fact which has been abundantly tested in practice, explains why the maximum heeling error is to be found when the ship's head is north or south by disturbed compass, and vanishes when the ship's head is at or near east or west by disturbed compass.

Give examples illustrated by curves of the heeling error, as observed on board an iron ship, and also the resulting co-efficients?

A. The two examples selected of H.M. ships Warrior and Defence illustrate the general feature of the heeling error being to windward.

In the Warrior, built with her head N. 3° E. magnetic, and armour-plated, in a N.W. direction there is a large amount of heeling error at the Standard compass on the quarter-deck. In the Defence, built with her head S. 47° W. magnetic, and armour-plated, S. 19° E. there is a much smaller amount of heeling error at the Standard compass in a similar position. The effect as resulting from the direction of the ship's head in building is thus clearly shown. It is also seen that the heeling error is greater at north than at south, and that the points of no heeling error are to the north of east and north of west.

(See Plate III. of the heeling error curves of these two ships, and the Tables of Deviation when heeled and upright, on the following page.)

H.M.S. WARRIOR, Lisbon, January 1868. H.M.S. DEFENCE, Lisbon, January 1868.

Warrior: Heeled 7½° to Port.	Warrior: Upright.	Warrior: Heeled 7½° to Starboard.	Ship's Head by Standard Compass.*	Defence: Heeled 7½° to Port.	Defence: Upright.	Defence: Heeled 7½° to Starboard.
° ′	° ′	° ′		° ′	° ′	° ′
11 15 E.	3 10 W.	14 0 W.	North	3 10 W.	1 50 E.	7 30 E.
10 30 –	3 0 –	13 30 –	N. by E.	3 50 E.	9 0 –	14 0 –
8 25 –	3 10 –	13 20 –	N.N.E.	9 40 –	13 30 –	18 20 –
5 35 –	4 10 –	13 0 –	N.E. by N.	14 30 –	18 10 –	21 30 –
2 0 –	5 30 –	12 30 –	N.E.	17 50 –	20 0 –	22 20 –
1 40 W.	6 50 –	12 0 –	N.E. by E.	18 50 –	20 20 –	22 0 –
5 40 –	8 20 –	12 0 –	E.N.E.	19 30 –	20 0 –	20 30 –
10 0 –	9 50 –	12 30 –	E. by N.	18 10 –	18 0 –	18 0 –
14 0 W.	11 30 W.	12 50 W.	East	17 20 E.	16 40 E.	16 20 E.
17 40 –	13 20 –	13 30 –	E. by S.	15 40 –	14 30 –	13 40 –
21 0 –	14 50 –	13 0 –	E.S.E.	13 30 –	12 10 –	10 30 –
23 0 –	15 50 –	11 40 –	S.E. by E.	12 0 –	9 40 –	7 30 –
22 30 –	16 0 –	9 30 –	S.E.	10 50 –	8 0 –	4 20 –
20 50 –	13 20 –	6 10 –	S.E. by S.	8 30 –	6 10 –	3 0 –
17 30 –	8 40 –	1 0 –	S.S.E.	7 30 –	4 30 –	2 0 –
12 0 –	3 25 –	5 20 E.	S. by E.	6 40 –	4 0 –	1 40 –
4 40 W.	3 10 E.	13 0 E.	South	6 10 E.	3 50 E.	0 30 E.
2 20 E.	10 20 –	21 30 –	S. by W.	5 30 –	2 30 –	0 40 W.
7 30 –	16 20 –	27 30 –	S.S.W.	4 30 –	1 0 –	1 30 –
12 20 –	20 30 –	30 10 –	S.W. by S.	2 10 –	0 40 W.	3 0 –
15 10 –	22 30 –	30 15 –	S.W.	1 0 W.	2 50 –	5 0 –
16 20 –	22 20 –	28 40 –	S.W. by W.	3 30 –	5 10 –	7 30 –
16 30 –	21 0 –	25 0 –	W.S.W.	6 30 –	8 10 –	10 0 –
15 40 –	18 20 –	20 30 –	W. by S.	10 30 –	11 30 –	12 20 –
14 30 E.	14 40 E.	15 50 E.	West	14 0 W.	14 10 W.	15 30 W.
13 0 –	11 30 –	10 30 –	W. by N.	16 30 –	17 0 –	17 30 –
11 0 –	8 0 –	5 20 –	W.N.W.	19 0 –	19 0 –	19 0 –
9 0 –	4 30 –	0 0 –	N.W. by W.	21 0 –	19 30 –	18 30 –
7 0 –	1 40 –	5 0 W.	N.W.	21 30 –	18 40 –	16 30 –
6 0 –	0 50 W.	9 0 –	N.W. by N.	20 0 –	16 10 –	14 0 –
6 40 –	2 40 –	11 50 –	N.N.W.	14 30 –	11 30 –	7 20 –
8 30 –	3 40 –	13 30 –	N. by W.	9 30 –	5 30 –	1 40 E.

Resulting co-efficients when heeled to

A	B	C	D	E		A	B	C	D	E
° ′	° ′	° ′	° ′	° ′		° ′	° ′	° ′	° ′	° ′
+0 50	−14 43	+ 6 45	+8 9	+0 59	Port.	+1 47	+16 39	+2 49	+7 18	+1 50
+0 50	−14 33	− 3 34	+7 48	−0 24	*Upright*	+1 41	+16 26	−1 5	+7 4	+0 42
+0 44	−15 36	−13 37	+8 17	−0 45	Starbd.	+1 38	+16 27	−4 40	+7 0	−0 5

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* It must be understood that in swinging these ships when heeled, and as well as when upright, the deviations were observed with the deviation of the ship's head noted by the *disturbed* compass.

In examining these deviations and the co-efficients, what is there to be especially remarked?

A. The general statement given in the last answer that the co-efficient which depends on fore and aft action (B) remains unchanged, and that the great change which takes place in 𝔈 is confirmed.

In the Warrior, we find that C changes 20° 22′ in the whole 15° of heel, or a *mean* change of 1° 22′ for each degree of heel. In the Defence, C changes 7° 29′ in the whole 14½° of heel, or a *mean* change of 30′ for each degree of heel. In both ships when heeling to port, C changes from a — to a + sign, or the N. end of the needle is drawn to the high or windward side of the ship in both cases, and when heeling to starboard C increases the — quantity, or the needle is again drawn to the high or windward side.

But there are two small heeling errors which generally come in to disturb the perfect symmetry of the curves of heeling error.

Ships in general may be considered as if they had a soft iron keel, the southern part of which attracts the N. end of the needle. Thus, if the ship's head be north, and if the Standard compass be, as is usual, nearer the stern than the bow; when the ship heels to starboard the needle goes to port, if the ship heels to port the needle goes to starboard. This increases the usual heeling error at north, and diminishes it at south.* This is generally very apparent in the curves.

So also, ships may in general be considered as having a vertical stanchion of soft iron in front of and below the compass, so that when the ship's head is east a heel to starboard gives a + heeling error, a heel to port a — heeling error. This generally throws the point of intersection of the heeling curves to the north of east and to the north of west. This also appears from the heeling curves.

As the process of heeling a large ship to determine the amount of error is always difficult, and is necessarily an expensive and a tedious process; can we, by theoretical deduction, and observations of a simple kind, obtain the heeling error without actually heeling the ship?

A. Theory does come to our aid in this essential matter. We have seen that the whole heeling error is made up (1) from the effect of vertical induction in transverse soft iron; (2) from the effect of vertical induction in vertical soft iron; (3) from the amount of vertical permanent magnetism in the ship, acquired in the process of building; (2) and (3) are—at any one geographical position—inextricably mixed together, and therefore may be treated as arising from one cause.

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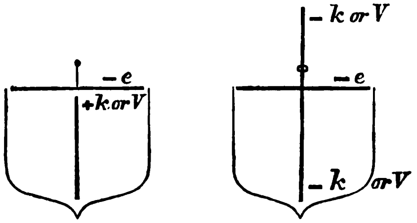
* **This part of the heeling error will be found fully treated a few pages on, in describing the effect of a soft iron rod *g*.**

The effect of every usual arrangement of soft and hard iron in producing the principal part of the heeling error or changes in $\mathfrak{C}$, may be thus represented by one or the other of the following types :—

Fig. 26.



where — *e* represents as before the transverse soft iron, which will evidently, as the ship heels over, produce a force to windward, or the high side of the ship, on the north end of the needle. If the rods + *k* or *V*, and — *k* or *V* represent soft iron, and the permanent magnetism of hard iron combined; then + *k* or *V* gives a force acting *downwards* on the north end of the needle, which, as the ship heels over, becomes a force to windward; and — *k* or *V* a force acting *upwards*, which, as the ship heels, becomes a force to leeward.

[The permanent magnetism of the ship will, as we have seen, act *downwards* if the compass is over the end of the ship which has been *south* in building; *upwards* generally if over the end which has been *north* in building.]

Now the amount of these forces (2) and (3) combined may be ascertained by observation, and expressed in terms of the co-efficient μ (*mu*);[*] (1) is known by the values of D and λ, and the whole being combined by a simple formula, with the known dip of the place, the angle of heel and the azimuth of ship's head by disturbed compass, gives the "heeling error."[†]

---

[*] The co-efficient $\mu = 1 + k + \frac{R}{Z}$; or $\mu Z = Z + kZ + R$—*i.e.*, it is that part of the vertical force (Z′) which is made up (1) of the earth's vertical force, (2) that caused by vertical induction *k*, and (3) that caused by vertical permanent magnetism; R representing a vertical bar-magnet above or below the compass, its S. end uppermost if R be +, its N. end uppermost if R be —; and Z representing the force of the earth's magnetism drawing the north point of the compass needle vertically downwards.

[†] The formula is conveniently put in the following form for correcting the deviation on any azimuth: the heeling error $= -\left\{ \mathfrak{D} + \frac{\mu}{\lambda} - 1 \right\} \tan \text{dip } \iota^\circ \cos \zeta'$. The heeling error is, therefore, zero, when $\zeta' = 90°$ or $270°$, *i.e.*, when the ship's head is E. or W. by compass; and is at a maximum when $\zeta' = 0$ or $180°$, *i.e.*, when the ship's head is N. or S. by compass.

Describe in fuller detail the co-efficient μ, as it is the principal element in the heeling error?

A. What we have to determine by observation with suitable instruments, as the co-efficient μ, is the ratio that the *mean* value of the vertical magnetic force at the place of the compass bears to the earth's vertical magnetic force.

Now if we call the vertical force of earth and ship, with the ship's head on any azimuth Z', and the earth's vertical force Z, then $\frac{Z'}{Z}$ is the amount sought for on that azimuth.

μ is the *mean* of *all* the values of $\frac{Z'}{Z}$ if made on equidistant azimuths; or, on *two* azimuths of the ship's head if made opposite to each other—and this renders μ easy of determination in a tide way when the ship is riding on the ebb and flood: μ also equals $\frac{Z'}{Z}$ when the ship's head is either east or west, and can thus be determined on *one* of these azimuths.

How is $\frac{Z'}{Z}$ determined?

A. $\frac{Z'}{Z}$ may be most simply obtained (except in low dips) by observing the vibrations of a dipping needle* placed with its face north or south (magnetic), in which position, when the needle is at east or west, it stands vertically: the needle is then disturbed so as to vibrate through a small angle—15° or 20° on each side the vertical—and the time of, say 10 vibrations observed from the mean of several sets. Then if T be time of 10 vibrations on shore, and T' the time of 10 vibrations at the place of the compass on board $\frac{T^2}{T'^2} = \frac{Z'}{Z}$; *i.e.*, if the squares of the time of the vertical needle's vibrations on shore be divided by the square of the time on board, the product is equal to the combined amount of the ship's vertical force and the earth's vertical force, the latter being represented by 1 or unity.[*]

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* By a dipping needle is understood a magnet bar capable of moving freely in a vertical direction, by having an axis at right angles to its length, and passing through its centre of gravity; the axis being supported on agate planes. When the needle is placed in the magnetic meridian, *i.e.*, with its face, or the axis pointing east or west, the needle assumes the direction of the line of force at the angle of the dip. When the needle is placed at right angles to the magnetic meridian, or with its face or axis pointing north or south, it stands vertically.

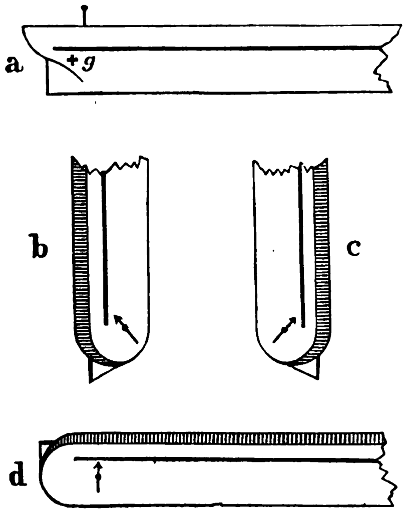
For purposes on board ship $\left(\text{to determine } \frac{Z'}{Z}\right)$, a simple instrument suffices to obtain the vibrations of the needle on each side the vertical; the needle need not exceed two and a half or three inches in length, but the workmanship of the axle and the agate planes requires to be good. Provision must also be made for levelling the instrument.

In the cases just given μ is supposed to have been derived from observations made on two or more equidistant points, or with the ship's head E. or W.: presuming then that the opportunity does not offer of placing the ship's head on the required azimuths, or that it is desirable to obtain the heeling error with the ship's head in one direction, how is μ then obtained?

A. If we have not the opportunity of observing the vertical force so as to enable us to obtain its *mean* value, the *individual* values observed will be affected by an arrangement of soft iron of the type represented by a rod g as in the accompanying figure (a).

The effect of this arrangement—exemplified by an iron deck, or the keel and bottom of the ship, symmetrically arranged with reference to the compass when the ship is upright—is to cause a heeling error to west when the ship heels to starboard (see fig. (b)): a heeling error to east when the ship heels to port (see fig. (c)). This error is at the maximum when the ship's head is north or south, and vanishes when the ship's head is at E. or W. (see fig. (d)).

Fig. 27.



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[*] Near the magnetic equator the values of the quantities Z′ and Z are so small that the value of the ratio $\frac{Z'}{Z}$ cannot be accurately ascertained by vibrating a dipping needle in an E and W plane; but nevertheless it may be determined with great accuracy by determining the dip and the horizontal force on board and on shore separately by means of a dipping needle and the vibrations of a horizontal needle, by the following formula :—

$$\frac{Z'}{Z} = \frac{H'}{H} \cdot \frac{\tan \text{dip}'}{\tan \text{dip}}$$

From this we get the heeling co-efficient to windward :—

$$-J = \frac{H'}{\lambda H} \cdot \tan \text{dip}' - (1 - \mathfrak{D}) \tan \text{dip} - \frac{g}{\lambda} \cos \zeta.$$

The effect of $+ g$ is therefore in general to give a heeling error to windward on northern courses and to leeward on southern courses.* Although g is not directly required for the determination of the heeling error, yet indirectly it is of great use in enabling us to determine μ from one observation as well as from several. It does not change with a change of geographical position: it is thus important to determine its value at some one place, and formulæ for so doing with examples are accordingly given.

What is in general the value of g?

A. This depends on the position of the compass. It is greatest when the compass is near the stern, and has then a + sign; it will act in an opposite direction, or have a *negative* sign near the bow; and it may be expected to disappear when the compass is near the middle of the ship. In a steering compass near the stern it may be assumed as $+ \cdot 200$. In a Standard compass in the ordinary position $+ \cdot 100$.†

Give now the simple graphic method in use for determining μ and $\frac{g}{\tan \text{dip}}$, from whence g is deduced.

A. 1. Describe a circle and suppose it divided as a compass card; draw the north and south and east and west lines—the north point being directed to the left hand. (*See following page.*)

2. Take on the circle the magnetic course on which each observation is made, and through each course draw a vertical line.

3. Select from the observed values of $\frac{Z'}{Z}$ that which has the least value, and indicate it by an encircled dot on the horizontal line N O S, at the point where it is intersected by the vertical line drawn through the magnetic course on which it was observed.

4. Find, then, the excess of each of the other values of $\frac{Z'}{Z}$, as taken from any convenient scale of equal parts, and lay them down on their respective vertical lines, measuring from the horizontal line N O S, marking the ends with encircled dots.

---

* The formula for any *one* azimuth is as follows :—

$$\mu = \frac{Z'}{Z} - \frac{g}{\tan \text{dip}} \cdot \cos \zeta.$$

† The value .100 gives about $\frac{1}{10}$th of the angle of heel, or 6′ for each degree of heel when at the maximum.

5. Draw a straight line, passing as nearly as possible through all the encircled dots;

then,

the ordinate to this line at E. or W., as measured from the horizontal line N O S, added to the least value of $\frac{Z'}{Z} = \mu$;

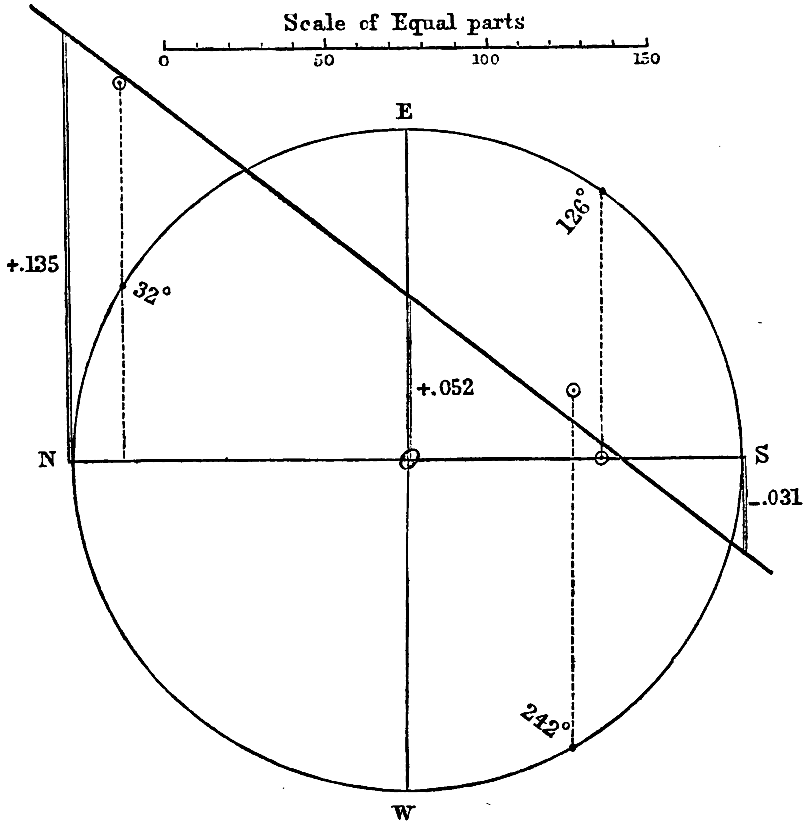
or

the mean of the ordinates at N. and S., as measured from the horizontal line N O S, added to the least value of $\frac{Z'}{Z} = \mu$;

and

half the difference of ordinates at N. and S. = $\frac{g}{\tan \text{dip}}$, which will be + if ordinate at N. is greatest.

Fig. 28.



In the above example the observations made in H.M.S. Achilles are again taken: $\frac{Z'}{Z}$, is determined on the magnetic courses 32°, 126°, 242°, $\frac{Z'}{Z}$ at the respective courses being .934, .814, 835 : $\frac{Z'}{Z}$ at 126° is therefore assumed the zero, and marked on the horizontal line N O S ; the length of the ordinate at 32° is then represented by .120 taken from a convenient scale of equal parts, and the length at 242° by .021. Then the distance from O to the straight line (=.052) added to the lowest value of $\frac{Z'}{Z}$—(.814)=μ or .866. Similarly the mean value of the distances from N. and S. to the straight line, or of +.135 and —.031 = +.052, which, added to .814, gives μ=.866, and $\frac{g}{\tan \text{dip}}$ = the half of +.135—(—.031) or +.083.

By calculation the values of μ and $\frac{g}{\tan \text{dip}}$ are respectively .867 and +.079.

Give the requisite formulæ for obtaining μ, g being unknown, and illustrate by examples the necessary computations.

A. It has been already stated that

$$\left.\begin{array}{l}\mu \text{ is the value of } \quad \frac{Z'}{Z} \text{ with ship's head east}\\ \text{,,} \quad\quad \text{,,} \quad\quad \frac{Z'}{Z} \quad \text{,,} \quad\quad \text{west}\end{array}\right\} \text{magnetic,}$$

,, mean value of $\frac{Z'}{Z}$ on any two *opposite* azimuths of ship's head,

,, ,, $\frac{Z'}{Z}$ on three or more *equidistant* azimuths,

and so far g is not required to be known.

If none of these conditions can be complied with, then, with a short additional calculation, μ (as also g) can be determined from observations of vertical force $\left(\frac{Z'}{Z}\right)$ on any *two* magnetic courses, as also with, of course, greater accuracy, from observations on *three* or more magnetic courses when *not* equidistant.

The formula for any *two* magnetic courses, as follows, is simple—

$$\mu = \frac{\frac{Z'_1}{Z}\cos\zeta_2 - \frac{Z'_2}{Z}\cos\zeta_1}{\cos\zeta_2 - \cos\zeta_1}$$

(The numbers 1 and 2 affixed to Z' and ζ, indicate the values appertaining to azimuths in the direct order from N. to S. by way of east, &c,)

With the same observations*

$$\frac{g}{\tan \text{dip}} = \frac{\frac{Z'_1}{Z} - \frac{Z'_2}{Z}}{\cos\zeta_1 - \cos\zeta_2}$$

---

* For the determination of g from observations of vertical force made on *two* azimuths, one observation at least should be made as nearly north or south as possible. If the observations are both made near east and west courses the formula fails.

Example of calculating μ and g from observations made on two magnetic courses. H.M.S. Achilles, Sheerness, October 13th, 1864.

Ship's head magnetic (ζ).	Time of 10 vibrations of vertical needle in plane at right angles to magnetic meridian on board (T').	Ditto on shore (T).	$\frac{T^2}{T'^2}$ or $\frac{Z'}{Z}$	
N. 32° E. or 32°	21.68 seconds	20.95 sec.	$\frac{438.9}{470.0}$	·934
S. 54° E. „ 126°	23.23 „	„	$\frac{438.9}{539.6}$	.814

then

$$\mu = \frac{.934\times.-588-.814\times.848}{-.588-.848}$$

$$= \frac{-.549-.690}{-1.436} = \frac{-1.239}{-1.436}$$

$$= .863$$

$$\frac{g}{\tan \text{dip}} = \frac{.934-.814}{.848-(-.588)}$$

$$= \frac{.120}{1.436}$$

$$= .083$$

$$g = 083\times 2.47, \text{ or } \tan \text{dip}$$

$$= +.205$$

The formulæ for obtaining μ and g from observations made on any *three* or more magnetic courses *not equidistant*, depending on the method of least squares, are too complicated for general use and are not introduced.

The solution, as annexed in a tabular form, will, however, be found very useful, and the necessary calculations simple in practice, by proceeding thus:

Place in vertical columns the following quantities, and denote the last four columns as I., II., III., IV. respectively:—

Ship's head magnetic or					I.	II.	III.	IV.
ζ	T'	T'^2	T	T^2	$\frac{T^2}{T'^2}$ or $\frac{Z'}{Z}$	$\cos\zeta$	$\cos^2\zeta$	$\frac{Z'}{Z}\times\cos\zeta$

then

$$\mu = \frac{\text{(Sums of) Col. I.}\times\text{Col. III.}-\text{Col. II.}\times\text{Col. IV.}}{\text{No. of Obs.}\times\text{Col. III.}-(\text{Col. II.})^2}$$

$$\frac{g}{\tan \text{dip}} = \frac{\text{No. of Obs.}\times\text{Col. IV.}-\text{Col. I.}\times\text{Col. II.}}{\text{No. of Obs.}\times\text{Col. III.}-(\text{Col. II.})^2}$$

Example of calculating μ and g from observations made on three or more magnetic courses.

H.M.S. Achilles, October 13, 1864.

					I.	II.	III.	IV.
ζ	T'	T'^2	T	T^2	$\frac{T^2}{T'^2}$ or $\frac{Z'}{Z}$	$\cos\zeta$	$\cos^2\zeta$	$\frac{Z'}{Z}\times\cos\zeta$
32°	21.68	470.0	20.95	438.9	.934	.848	+.719	.792
126	23.23	539.6	”	”	.814	—.588	+.346	—.479
242	22.93	525.8	”	”	.835	—.469	+.220	—.392
				Sums	2.583	+.848	1.285	+.792
						—1.057		—.871
						— ·209		—.079

then

$$\mu = \frac{2.583\times1.285-(-.209\times-.079)}{3\times1.285-(-.209)^2}$$

$$= \frac{3.319-.016}{3.855-.044} = \frac{3.303}{3.811}$$

$$= \mathbf{.867}$$

$$\frac{g}{\tan \text{dip}} = \frac{3\times-.079-2.583\times-.209}{3.811}$$

$$= \frac{-.237-(-.540)}{3.811} = \frac{.303}{3.811}$$

$$= +.079$$

$$g = +.079\times2.47 \text{ or } \tan \text{dip}$$

$$= \mathbf{+.196}$$

If we wish to determine μ from observations on *one* course, as in dock for example, g must be either known or assumed, unless the ship's head is at or near east or west magnetic, then

$$\mu = \frac{Z'}{Z} - \left(\frac{g}{\tan \text{dip}} \times \cos\zeta\right)$$

Example.

H.M.S. Achilles, October 13*th*, 1864. *Sheerness.*

Ship's head magnetic or ζ.	T'	T	$\frac{T^2}{T'^2}$ or $\frac{Z'}{Z}$	g **known or assumed** = .200	
	sec.	**sec.**			
N. 32° **E.**	21.68	20.95	$\frac{438.9}{470.0} = .934$	$\frac{g}{\tan \text{dip}} = \frac{.200}{2.47}$	$= .081$

$$\mu = .934-(.081\times.848)$$

$$= .934-069$$

$$= \mathbf{.865}$$

Having now found μ, what is the next step to be taken in the computation, in order to obtain and apply the heeling error ?

A. The effect of heeling is, as we have seen, to add to the deviation when observed with the ship upright, or rather to the co-efficient ℭ, a term composed of μ, 𝔇, λ, multiplied by the tangent of the dip, the angle of heel, and by the cosine of the azimuth of ship's head by disturbed compass. This is the "heeling error;" but it is found more convenient in practice to compute the value of this term, or its amount in degrees of deviation, for *one* degree of heel when the ship's head is N. or S. by disturbed compass; *i. e.*, when the heeling error is at its maximum, and this term is known as the "*heeling co-efficient.*"[*]

If, for example, therefore, we had determined the "heeling co-efficient" of the Achilles to be 0° 30′ to windward, the following would be the results if the ship were swung heeled 10° to starboard and 10° to port, when her head was N. or S.[†]:—

	B.	C.	D.
	° ′	° ′	° ′
Heeling 10° to port	+19 54	−1 37	+6 58
Upright	+19 54	+3 23	+6 58
Heeling 10° to starboard	+19 54	+8 23	+6 58

From the values of μ, 𝔇, and λ, we may also determine how much of the heeling co-efficient arises from transverse soft iron, represented by a and e (figs. 19, 20, page 52), and how much from vertical soft iron and hard iron combined, represented by k (fig. 26).

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[*] Or χ of the 1st and 2nd editions of Admiralty Manual, and —. J of 3rd edition, foot note, p. 141.

[†] In this example, to avoid complication, the effect of g is not considered.

Computation of Heeling Co-efficient. H.M.S. Achilles, at Sheerness, continued.

Give the formula for the heeling co-efficient, as also for its parts, arising from the transverse iron and from vertical iron, with examples of the computation.

ANSWER.

Heeling co-efficient

$$\begin{aligned} &= \left(\mathfrak{D} + \frac{\mu}{\lambda} - 1\right) \times \text{tan dip} \begin{cases} + \text{ to weather, or high side of ship.} \\ - \text{ to lee , or low ,,} \end{cases} \\ &= \left(.121 + \frac{.867}{.810} - 1\right) + 2.47 \\ &= (.121 + .070) \times 2.47 \\ &= +.472 = 0^\circ\ 28' \text{ to high side} \begin{cases} \text{for each degree of heel when} \\ \text{ship's head north or south.} \end{cases} \end{aligned}$$

Part of heeling co-efficient, *from vertical induction in transverse iron.*

$$\begin{cases} = \left(\mathfrak{D} + \frac{1}{\lambda} - 1\right) \text{tan dip} \begin{cases} + \text{ to weather, or high side of ship.} \\ - \text{to lee , or low ,,} \end{cases} \\ = (.121 + 1.234 - 1) \times 2.47 \\ = (.121 + .234) \times 2.47 \\ = + .877 = 0^\circ\ 52' \text{ to high side, for each degree of heel, \&c.} \end{cases}$$

Part of heeling co-efficient, *from vertical induction in vertical iron, and from vertical permanent magnetism.*

$$\begin{cases} = \left(\frac{\mu}{\lambda} - \frac{1}{\lambda}\right) \text{tan dip} \begin{cases} + \text{ to weather, or high side of ship.} \\ - \text{ to lee , or low ,,} \end{cases} \\ = (1.070 - 1.234) \times 2.47 \\ = - .405 = 0^\circ\ 24' \text{ to low side, for each degree of heel, \&c.} \end{cases}$$

In this example of Achilles we see that the mean vertical force caused by permanent magnetism and vertical induction in vertical iron acts *upwards*, and repels the N. end of the needle to *leeward;* arising, as explained, p. 90, from the ship's head in building being nearly in a S.E. direction, and the Standard compass far art (one-ninth of the ship's length from the stern). This force acts in antagonism to that arising from vertical induction in transverse iron, and thus μ is less than unity, and there is comparatively a small heeling error.

If the ship had been built with head in a northerly instead of in a southerly direction, or in the same ship at a position near the bows, the two forces would conspire; in the first case μ would be greater than unity, in the second case g would be reversed in sign, and in each case the heeling error would be comparatively large. This deduction from theoretical considerations is well exemplified in the Achilles: at a compass placed on the forecastle, one-sixth the length of the ship from the bow, we have the following comparative results:—

At compass	One-ninth ship's length from stern.	One-sixth ship's length from bow.
$\mathfrak{D}$	$+.121$	$+.128$
λ	$.810$	$.831$
μ	$.867$	1.217
Heeling co-efficient to windward	$+0^\circ\ 28'$	$+1^\circ\ 29'$
Part of ditto from vertical induction in transverse iron.	$+0\ \ 52$	$+0\ \ 49$
Part of ditto from vertical induction in vertical iron and permanent magnetism	$-0\ \ 24$	$+0\ \ 40$
Part of ditto from g	$+.196$ (or 12′)	$-.172$ (or 10½′)

With these values of the heeling co-efficient and g, how would you find the heeling deviation for a given number of degrees of heel (10°) on any given course?

A. The deviation for a given course at any angle of heel equals the deviation when upright, *plus* the heeling co-efficient + J or − χ at that angle of heel multiplied by the cosine of the given course, *minus* $\frac{g}{\lambda}$ at the same angle of heel multiplied by the square of the cosine of the given course.*

---

* *i.e.*, $\delta i = \delta + J i^\circ \cos \zeta' - \frac{g}{\lambda} i^\circ \cos^2 \zeta'$, where J = the heeling co-efficient to leeward. See Admiralty Manual, 3rd edition, p. 141.

In this example the effect of c is omitted; c and g may be both disregarded in a well placed compass in the ordinary class of iron ships: both terms have, however, a sensible value in compasses placed near the extremities of an iron ship.

Example.

$$\text{At } \textit{after} \text{ compass of Achilles} \begin{cases} \text{Heeling co-efficient for } 1^\circ = -\ \overset{\circ}{0}\ \overset{\prime}{28} \\ \quad ,, \qquad\qquad\qquad\quad 10^\circ = -\ \mathbf{4\ 40} \\ \frac{g}{\lambda} \text{ for } 1^\circ = \frac{.196}{.810} = .242 = +\ 0\ 14\tfrac{1}{2} \\ ,, \quad 10^\circ \qquad\qquad\qquad = +\ \mathbf{2\ 25} \end{cases}$$

$$\text{At } \textit{fore} \text{ compass of Achilles} \begin{cases} \text{Heeling co-efficient for } 1^\circ = -\ 1\ 29 \\ \quad ,, \qquad\qquad\qquad\quad 10^\circ = -\mathbf{14\ 50} \\ \frac{g}{\lambda} \text{ for } 1^\circ = \frac{-.172}{.810} = -.212 = -\ 0\ 12\tfrac{1}{2} \\ ,, \quad 10^\circ \qquad\qquad\qquad = -\ \mathbf{2\ \ 5} \end{cases}$$

	Achilles.—*After* compass.			Achilles.—*Fore* compass.		
	Heel. co-eff. for 10° × cosin ζ'.	**$-\frac{g}{\lambda}$ for 10° × cos $2\zeta'$.**	**Heeling error.**	**Heel. co-eff. for 10° × cosin ζ'.**	**$-\frac{g}{\lambda}$ for 10° × cos $2\zeta'$.**	**Heeling error.**
	° ′	° ′	° ′	° ′	° ′	° ′
North	−4 40	−2 25	−7 5	−14 50	+2 5	−12 45
N.E. and N.W.	−3 18	−1 12	−4 30	−10 30	+1 2	− 9 28
E. and W.	0	0	0	0	0	0
†S.E. and S.W.	+3 18	−1 12	+2 6	+10 30	+1 2	+11 32
South	+4 40	−2 25	+2 15	+14 50	+2 5	+16 55

On change of geographical position, how is the heeling error affected?

A. The part arising from $\frac{g}{\lambda}$ remains unaltered in all latitudes.

That part which depends on permanent vertical force varies inversely as the earth's horizontal force, and therefore will diminish as we approach the magnetic equator, and increase again as we pass it.

That part which depends on the induction of the vertical force in soft iron varies as the tangent of the dip, and therefore becomes zero, and changes its sign as we pass the equator; unless, therefore, we know the proportion of the vertical force which arises from permanent magnetism to that which arises from induction in soft iron, we cannot predict with much confidence the change which will take place in the heeling error, and hence the desirability of determining independently the heeling error with the ship's head N. and S., whenever an opportunity offers on any distant voyage.

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† The calculation of cos $2\zeta'$ for 0°, 45°, 90°, &c., is simple, as cos $2\,45^\circ = \frac{1}{2}$, and there are no changes of sign.

SECTION XI.

On the preparation for, and selection of place for compasses in iron ships, and the mechanical correction of the deviation.

Does experience concur with theory in showing that in the behaviour of the compasses of an iron ship much depends on the selection and preparation of a proper place for the compass ?

A. It does: for in the case of compasses placed simply with reference to the convenience of the steering apparatus and the helmsman the deviations are frequently found to be excessive and irregular; they thus require correction by powerful magnets placed within a short distance, and when so corrected, large errors may be introduced by even slight changes in the magnetism of the ship or of the magnets—the compasses in such positions frequently become dull from the great diminution of directive force, and there is often a large heeling error. The error depending on the length of the needles is also frequently increased.*

On the other hand, if the compass be in a place selected for its freedom from magnetic disturbance, and for the uniformity of the amount and direction of the magnetic force in its vicinity, the deviations will be comparatively small and regular, correction by magnets may not be necessary, or if necessary, will not be much affected by slight changes in the magnetism of the ship, the heeling error will be moderate in amount, and the needle will not become dull from the diminution of directive force.

In addition to the rules already given at pp. 2, 5, for the guidance of the seaman, the following are worthy the attention of the naval architect and those superintending the equipment of the ship:—

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* The following extract from the "Second Report of the Liverpool Compass Committee," p. 20, although written in 1856, may be still repeated from its constant neglect. "The error in the first position of the binnacle was 101°. As the ship was going to the East Indies, the compass adjuster objected to compensate so large an amount, and the binnacle was then placed three feet forward; here the error was reduced to two points. In another and much larger ship, the compass in the first position of the binnacle deviated 14 points; on moving it a little further forward, the error was reduced to 2½ points."

See also Royal Society's Proceedings for 1869, on the loss of the iron ship Glenorchy.

1. In all designs for the construction of iron ships, a place to be prepared for the Standard compass, and to be shown in the plans.

2. The Standard compass not to be within half the breadth of the ship from the rudder-head and stern-post or iron-cased screw well: not to be nearer an iron deck or iron deck-beams than five feet.

3. In ships built head near north, the Standard compass to be as far *forward* as the requirements of the ship will permit. In ships built head near *south*, to be as far aft as the requirements of the ship will permit, subject to rule 2. In ships built nearly *east* or *west*, the Standard compass not to be near either extremity of the vessel.

4. To be as far as possible from transverse iron bulkheads.

5. As far as possible, no masses of iron—as boilers, engines, bulkheads, stanchions—should be placed below the compass, or within 55° of the vertical line through the centre—the angle being drawn from the compass as centre to the centre of the mass in question.*

What are the important principles to be borne in mind in connection with the compasses, in building an iron ship?

A. They are these: †

1. That when circumstances compel the compasses to be placed in the after part of the ship, it is *undesirable* that she should be built head north, or near it; and that on the whole the *most desirable* position to build an iron ship which is to remain in the northern hemisphere is with her head south, or near it. If the ship is to go to the southern

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* Investigation has shown that the effect of a sphere of iron within this cone is prejudicial by diminishing the directive force and increasing the heeling error to windward; when without the cone it would be beneficial in both respects. Hence the recommendation.

With reference to the magnetic character of boilers or tanks, it has been stated that the effect is the same as if they were solid bodies, on the assumption that magnetism exists entirely upon the surface of iron masses. This is not the case; it is, however, true that the effect of hollow masses of iron increases very rapidly with the increase of the thickness of the iron, so that the limit of thickness is speedily reached when the effect of the body is sensibly the same as if it were solid: for example, in a tank 4 feet in diameter and $\frac{1}{16}$th of an inch thick, the effect is about $\frac{1}{3}$rd of a solid mass of the same size; in a similar-sized tank $\frac{1}{8}$th of an inch thick, the effect would be about $\frac{1}{2}$ that of a solid mass. See a valuable investigation by Mr. Archibald Smith, in the Phil. Trans. for 1865, pp. 304—318.

† This, and the preceding question and answer, are in substance the instructions for the general guidance of the constructors of Her Majesty's Ships, as issued by the Controller's Department.

hemisphere there seems to be some advantage in building her with head east or west, or near those points of the compass.*

2. Every iron ship should as much as possible after launching—that is during the progress of her first equipment—be kept in a position opposite to that of building.

3. When an iron ship is armour-plated after launching, the operation should as far as possible be performed with her head in an opposite direction to that of building.†

On the mechanical correction of the deviation.

What is the object of applying magnet bars to correct the larger deviations of the compass in iron ships, and on what principles does their application depend?

A. The object is twofold: first, the reducing the larger semicircular deviations, which are embarrassing where they exceed a certain amount;‡ and secondly, and more especially, the equalising the directive force on different courses. The principles are obvious, for it has been seen that all the polar forces acting in a ship may be represented by an imaginary magnet, and it is therefore certain, from well known laws of magnetic action, that we can neutralise the effect of these disturbing forces, by introducing a real magnet whose force has the same magnitude, but acts in an opposite direction.

What are the embarrassments produced by large deviations, and what is meant by equalizing the directive force on different azimuths?

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* This paragraph, so far as it relates to ships built head north or south, must be considered as applying to those built in the northern hemisphere; it would be reversed for those built in the southern hemisphere. It is well here to remember, that the effect of steam machinery (as observed in the wood screw ships of the Royal Navy) is to give a + B of 6° to 10°, and a small + D (½°), which latter occasionally changes to a — sign in small vessels, when the compass is near the screw shaft. The effect of cast-iron guns, even in three-decked ships of 120 guns, was very small; the large deviations sometimes recorded in the old sailing ships of war, arose chiefly from the spindle of the capstan, or from arm stands placed too near the compass.

† The law, that "the north point of the needle is attracted to that part of the ship which was south in building," extends to the armour plating of either iron or wood built hulls; consequently, in those ships which have been plated after launching, and in a different position from that of building, the direction of the semicircular force is generally intermediate between the two relative positions of the head in building and in plating. Hence the recommendation in the text.

‡ As a general rule it is recommended that an iron (or composite) ship should not proceed to sea from a home port with an original semicircular deviation at the Standard compass exceeding 15°. If it exceeds that amount a reduction should be made by magnets.

A. If the deviations are large in amount, the angular movement in azimuth of the ship's head is not represented by a similar apparent angular movement of the compass. For example, in H.M.S. Warrior, when her head changes by compass from S.S.E. to S.S.W., or through an angle of 45°, the actual angular movement of her head by the horizon is 7 points, or nearly 80°. This is of itself embarrassing to the seaman; also in the same case, the earth's directive force has been reduced nearly one-half by the antagonism of the ship's force with her head in those azimuths. This gives sluggishness to the compass and increases the effect of friction and other disturbing causes.* The neutralization of the ship's polar force, *i.e.*, the reduction of the semicircular deviation by the introduction of an opposing magnet, necessarily allow the directive force of the earth to act equally on the ship's compass needle in all azimuths.

Is the necessity for employing magnets as correctors greater now than it was in former times of iron ship-building?

A. Yes; the greater introduction of iron for beams, decks, transverse bulkheads, and armour-plating, has conduced to the great decrease of directive force of the compass needle in all parts of the ship. This is shown by the small values of λ. The average force, as before stated, is thus commonly reduced one-fourth from its value on shore or in a wood-built ship, or to three-fourths of its proper value; and the force, when the ship's head is in directions opposite to that of her head while building, is, in many cases, reduced to about one-third of that average, or to one-fourth of its proper value, and in some cases is even reversed: these facts not only show the necessity of correction by magnets, but also the necessity of employing the most perfect compasses in the modern types of iron ships.

Under what conditions are magnets applied, with reference to the magnetic character of the ship?

A. The mechanical correction of the compass—in analogy with the errors of the compass—is naturally divided into three parts; and we must consider separately the correction of the semicircular deviation, the quadrantal deviation, and the heeling deviation;—of these, the most important for consideration, both from its magnitude and from its inconvenience to the navigator, as well as happily the most easily corrected, is the correction of the semicircular deviation.

This correction may be made either with or without calculation of the co-efficients B and C; the process without calculation is purely tentative—it was originally devised by the Astronomer-Royal, and is in

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*** It is well to remember that the loss of directive force in the uncorrected compasses of iron ships, occurs in those courses which are on and near to the direction of the ship's head in building; in other words, the magnetic force of the ship is then in direct antagonism to the earth's directive force.**

common use in the mercantile marine: the process by calculation is that generally employed in the Royal Navy.

How are magnets applied to correct the semicircular deviation?

A. The tentative process, or that without calculation, is as follows:—

Two chalk lines are to be drawn on the deck from a point exactly under the compass—one line fore and aft, and the other at right angles to it. The ship's head is then to be placed on one of the cardinal magnetic points, as determined by a shore bearing, or by the known deviation of the compass to be corrected.

With the ship's head N. or S. magnetic, place a bar magnet athwart ships, with its centre on the fore and aft chalk line (either before or abaft the compass), the N. or marked end of the magnet being directed to the starboard side of the ship if the compass north deviates to the right, and *vice versâ*: move now the magnet* to or from the intersection of the chalk lines till the needle points correctly. *The deviation represented by the co-efficient* 𝕮 *is neutralised by this operation.*

With the ship's head then directed east or west magnetic, place a bar magnet in a fore and aft direction, with its centre on the transverse line, (either to port or to starboard of the compass), the N. or marked end of the magnet bar being directed aft if the compass north deviates to the right, and *vice versâ*; move now the magnet to or from the intersection of the lines till the needle points correctly. *The deviation represented by the co-efficient* B *is neutralized by this operation.*

If the ship's head be now placed on the two opposite cardinal points, it may be found that a small deviation still exists; in which case the magnets may be again slightly moved on their respective lines to reduce this residual error within the smallest limits.†

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* It may be necessary, if the compass is well elevated above the deck, to use two or more magnets—these may be placed on both sides of the compass, or all on one side; the magnets must of course be kept parallel, and should not be close to each other. This remark applies equally to magnets placed fore and aft to correct B.

As a general rule, it is not expedient to place the correcting magnet bar within twice its length of the compass needle.

† In making this correction, it is advisable to leave about 1½° of the semicircular deviation uncorrected at the N. and S. points, and about ½° at the E. and W. points, the deviation so left to be westerly if the ship has been swung from left to right, easterly if from right to left. This small correction arises from the noticeable fact that when an iron ship is swung to the left, a temporary + A and + E are introduced, and when to the right a temporary — A and — E. These it is, of course, best to leave uncorrected.

We are indebted to M. Gaussin, of l'Ecole du Génie Maritime, for this fact, which has been verified by the discussion of numerous deviation tables of H.M. Ships. It doubtless arises from the slowness of soft iron in receiving or parting with its full

The above process may be performed by calculation if we know $\mathfrak{B}$ and $\mathfrak{C}$, and either find or estimate λ in the following manner:

Find the distance from a compass to be corrected, on shore, at which the magnet placed E. and W. with its centre N. or S. of the compass will produce a deviation of which the *natural tangent* is $\lambda\ \mathfrak{C}$. Similarly find the distance at which another magnet placed in the same way will produce a deviation of which the natural tangent is $\lambda\ \mathfrak{B}$. These are the distances measured from the centre of the needle to fix the magnets on board: the first for the magnet to be placed transversely on the fore and aft line; the second for the magnet to be placed fore and aft on the transverse line.*

Can the semicircular deviation be corrected by one magnet?

A. Yes, and this is a very neat, convenient, and secure method. It is especially applicable for the correction of the Standard compass, both on account of the comparatively small changes in the ship's magnetism at that selected position; and also on account of the difficulty of reducing large deviations by magnets placed on the deck, from the height to which this compass is necessarily raised.†

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charge of induced magnetism, and shows itself as described in soft iron of the *a* and *e* type.

* In the last, and early part of the present century, considerable attention was paid to the properties of magnet bars. Some diversity in opinion will, however, be found among the experimental magneticians of these times as to the best proportions of form. For rectangular bars, as now applied to correct the semicircular deviation, the following will be found convenient proportions, and which does not differ much from a mean value of the several authorities.

Breadth of magnet to be $\frac{1}{10}$th the length, thickness of magnet $\frac{1}{4}$th the breadth. On shore, average magnet bars of these proportions, and of the undermentioned sizes and combinations, will, when free of all loose magnetism at the several given distances, correct the Admiralty Standard Compass for the appended amount of deviation in degrees approximately.

Distance. Ft. In.	One 10-inch bar. °	Two 10-inch bars. °	One 12-inch bar. °	Two 12-inch bars. °	One 18-inch bar. °	Two 18-inch bars. °	Distance. Ft. In.
1 8	16	28					1 8
2 0	12	19	17	26	40	55	2 0
2 3	10	15	13	20	31	44	2 3
2 6	8	12	10	15	24	38	2 6
2 9	6	9	8	11	19	31	2 9
3 0	5	8	6	9	15	26	3 0
3 3	4	6	5	7	13	20	3 3
3 6	3	5	4	6	10	16	3 6
4 0					7	11	4 0

† In the Royal Navy, the support of the Standard compass is generally a cylindrical pillar of mahogany or teak, and in this pillar a magnet (or two, if required) from 10 to 12 inches long is easily inserted in any required azimuth and at

We must in this method first find or estimate λ, and obtain $\mathfrak{B}$ and $\mathfrak{C}$ by any of the methods described.* Then find the angle, of which the natural tangent is $\sqrt{\mathfrak{B}^2 + \mathfrak{C}^2}$ (see page 51) multiplied by λ, and call this angle M: find also the angle of which the nat: tan: is $\frac{\mathfrak{C}}{\mathfrak{B}}$ and call this angle N.

Take a bar magnet of convenient size (10 or 12 inches long) to pass nearly, but not quite, through the supporting pillar; and then in a position on shore, free from the influence of iron, place this magnet in an east and west direction, with its centre due north or south (magnetic) of a compass. Move the magnet to or from the compass till it produces a deviation M, and note its distance from the centre of the compass.

Then take the magnet on board, and place it, with its axis, horizontal, and its centre at the above noted distance immediately below the centre of the compass to be corrected; the axis of the magnet making an angle N with the fore and aft line, taking care to place the N or marked end of the magnet in a direction pointing to that part of the ship toward which the N. end of the needle is attracted, *i.e.*, if the semicircular deviation is composed of $+\mathfrak{B} + \mathfrak{C}$, or if the force of the ship is on the starboard bow, the N. end of the magnet should point in that direction; if of $-\mathfrak{B} - \mathfrak{C}$, the N. end of the magnet should point to the port quarter of the ship, and so on: in other words, the magnet is the antagonistic force to the ship's horizontal force, both in amount and direction.

The magnet as now placed has corrected the whole semicircular deviation, but in a newly built ship, as the semicircular deviation is generally

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any required distance below the card, and when in position securely capped at its ends. As the binnacle or steering compasses in the Royal Navy are always elevated about 3 feet 9 inches above iron deck beams, it is found convenient to form their supports of a plain hollow cylinder of wood, with a clear internal space to admit a 12 inch magnet. The correcting magnet or magnets can then be securely fixed inside, without being liable to displacement, accidental reversal of poles, or unknown removal; accidents frequently incidental to magnets secured *on* the deck. The reversal of the position of the poles not unfrequently happens to magnets let *into* the deck, after caulking or other repairs, through the ignorance of workmen.

* Bearing in mind that "magnet compensation is seldom so perfect as to dispense with the necessity for a table of deviations" (*Liverpool Compass Committee, 2nd Report*, p. 27), the object aimed at is to reduce the semicircular deviation to a small and manageable amount and not its entire removal; great accuracy in the determination of $\mathfrak{B}$ and $\mathfrak{C}$ is not required, and this preliminary determination need not therefore be made by the complete process of "swinging." $\mathfrak{B}$ and $\mathfrak{C}$ determined from observations of deviation and magnetic force on one azimuth; or from observations of deviation in one quadrant or in one semicircle, while the ship shifts from dock or swings at anchor, furnish sufficient data for the determination of $\mathfrak{B}$ and $\mathfrak{C}$.

in process of diminution, it is desirable to leave a few degrees uncorrected.*

Are moveable magnets employed for correcting semicircular deviations?

A. For ships making voyages to the southern hemisphere, and in which the steering compasses are placed very near to the rudder-head, and the vertical iron in the stern of the ship, moveable magnets are a necessity, in order to counteract the rapid changes in the inductive magnetism of those vertical masses on change of magnetic latitude.† These magnets are fitted accurately in frame work on the fore and aft and transverse sides of a square binnacle, and arranged to be moved in a vertical direction by screw racks. To correct the compass errors, the ship's head is placed on a cardinal point, as determined by astronomical observations, and the corresponding arrangement of magnets moved up or down till the compass points accurately.

How is the quadrantal deviation commonly corrected?

By a mass of soft iron placed on the same level as the compass needle,

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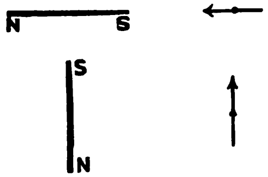
* It will be seen that in correcting the semicircular deviation, the magnets are always kept in a horizontal plane, and never placed end on to the compass, but broadside on. This is to avoid the introduction of vertical force when the ship heels.

The effect of a magnet placed end on is double that of a magnet placed broadside on at the same distance.

In the first case, the force of the magnet is proportional to *twice the length* of the magnet divided by the cube of the distance between the centre of the magnet and the centre of the needle.



In the second case, the *resultant* of the polar forces of the magnet acts in a direction parallel to S N, and is proportional to the *length* only of the magnet divided by the cube of the distance between the centre of the magnet and the needle.

The above is only strictly true so far as relates to the action of a magnet bar on a magnetic particle, and not on a needle of definite length. If, however, the needle be small and the magnet not very close, the effects are (nearly) as described.

† It has been proposed to neutralize the injurious effect of this arrangement by fixing in the ship a vertical bar of iron in front of the compass, at such a distance that the inductive changes which occur in it shall, as nearly as possible, balance the changes in the vertical masses abaft the compass. This compensating bar, which may vary from two to three inches in diameter, it is proposed should reach from the keel of the ship to about the height of the binnacle. In a modified degree, this arrangement, as originally proposed by Mr. Rundell, secretary of the Liverpool Compass Committee, was carried out in a few ships at Liverpool under his superintendence, and found beneficial. It is an arrangement requiring much skill to carry out successfully.

either on the starboard or port, or both sides, according to the amount of + D that requires to be corrected; or on the fore and aft sides of the compass in the very unusual event of D. being negative.*

The small quadrantal values of 2° to 3° are commonly corrected by a small iron chain enclosed in a box, but for larger deviations cylinders of cast iron, with hemispherical ends, have been successfully employed. As these correcting masses of iron must be placed very close to the compass, to produce the required attraction on either end of the needle as the ship revolves in azimuth, great care is required in the selection or construction of the correctors that no permanent magnetism be allowed to exist.

The cast-iron cylinders introduced by the Liverpool Compass Committee were of two sizes—the larger 12 inches long by 3¼ inches in diameter, the smaller 9 inches long by 3 inches in diameter: a *pair* of these cylinders corrected the following amount of quadrantal deviation (see 3rd Report, pp. 34 and 63).

End of Cylinders from Centre of Compass.	Pair of Small Cylinders.		Pair of Large Cylinders.	
Inches.	°	′	°	′
7	10	10	12	50
8	6	17	8	27
9	4	8	5	57
10	2	52	4	17
11	1	58	3	4
12	1	24	2	15

With single-needle compasses a large octantal error is caused by the correctors; *i.e.*, a deviation having eight maxima—four easterly and four westerly—as the ship is turned through 360°. Compasses to which the correction of soft iron is applied should therefore have two or four needles arranged, as described at page 3.

The effect of correctors can be easily ascertained by trial on shore, placing them at the level of the compass in a line directed to its centre, the line making an angle of 45° + ½ D. with the N. and S. line; and then moving the correctors to and from the compass till the required deviation D is produced. The distance on shore, which produces a quadrantal deviation — D will in a similar position on board correct a quadrantal deviation + D.

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* Masses of iron of a spherical or cylindrical shape, placed near the level of the compass in a fore and aft line, are beneficial in increasing the directive force, but prejudicial in increasing the quadrantal deviation; if placed on the port or starboard side they are doubly beneficial, as they both increase the directive force and diminish the deviation. Iron masts, which may be compared to a vertical cylinder of infinite length, do not increase the directive force, but increase the quadrantal deviation, and are, so far, slightly prejudicial. It is here understood that the compass is not placed near the heel or head of the mast, which are, of course, powerful poles.

After the semicircular deviation has been corrected by magnets, place the ship's head on one of the quadrantal points, N.E., S.E., S.W., N.W. magnetic, then place the correctors on the same level and at equal distances on the starboard and port sides of the compass needle, and move them to or from the compass till the needle points correctly; test the correction by placing the ship on one or more of the other quadrantal points.

Note.—The soft iron correction of D is not affected by any change of magnetic latitude; when once made, it should remain at all times and places perfect.

Can the quadrantal deviation be corrected without the application of soft iron?

A. Yes, by a correction depending on the following circumstances:—

1st. That the quadrantal deviation of an iron ship, except in rare and exceptional cases, is always *positive.*

2nd. That the effect of two compasses, placed side by side, on each other, is to produce a *negative* quadrantal deviation.

If, therefore, we take two compasses of precisely equal strength, and place them in the usual double binnacle, *i.e.*, one to starboard and one to port, in a position where, from no iron being near, the deviation of one compass is sensibly the same as that of the other [the semicircular deviation being then corrected by the usual fore and aft and transverse magnet placed in a central position between the two compasses], then the *negative* quadrantal deviation produced by the needles corrects the *positive* quadrantal deviation produced by the ship.

How are the distances at which the compasses should be placed from each other to correct a given quadrantal deviation to be ascertained?

A. Either by placing the compasses on shore in a line making an angle of $45° + \frac{1}{2}\lambda D$ with the N. and S. line, and moving them to and from each other till the deviation $\lambda\mathfrak{D}$ is produced, and measuring the distance;

Or, by placing them on shore in an E. and W. line from each other, and then turning one of the cards till its needle is directed to the other card, and then moving this card to and from the other till it produces a deviation whose nat: tangent is four-thirds of D; these several distances are those to place them from each other on board ship.

If the quadrantal deviation is unknown (the semicircular deviation being corrected), place the ship's head on a quadrantal course and move the compasses to and from each other till the quadrantal error is corrected.

Under what circumstances can this method be advantageously employed, and what are its disadvantages as compared with soft iron correction?

A. When the quadrantal deviation is very large—as between decks in iron-plated ships—its mechanical correction by soft iron becomes impracticable from the large amount of iron required, the close proximity to the compass at which it must be placed, and the difficulty of freeing the correctors entirely from permanent magnetism.

The disadvantages are that it is not perfect in all magnetic latitudes, as is the case with the soft iron correctors, for, as the effective power of each needle in correcting a quadrantal deviation is inversely in proportion to the horizontal force of the earth at the place, a quadrantal deviation so corrected would reappear to nearly half its amount on the vessel reaching the magnetic equator. In lower magnetic latitudes, *i.e.*, when the horizontal force is greater than in the place of correction, the correction is nevertheless beneficial, though insufficient; in higher latitudes the quadrantal deviation is over corrected. By a provision for moving the compasses to and from each other, so as to adjust for the mutual distance, these defects are remedied.

Correction of the heeling deviation.

We have seen that the heeling error can be determined by observations made when the ship is upright, and thus a great expenditure of time and labour avoided: knowing the heeling error, how can it be corrected?

A. By placing a *vertical* magnet exactly under the centre of the compass at a given distance to be ascertained by experiment. If, as is generally the case, the heeling error is to *windward*, the N. or marked end of this magnet is placed uppermost; if to *leeward*, the S. end uppermost.*

It must, however, be remembered that the correction for the heeling error is only, in general, exact for one latitude, and must be tested on any considerable change of latitude by observing the effect of the heeling of the ship on a N. or S. course, or by observing the vertical force, *i.e.*, determining μ.†

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* In the Royal Navy, the general practice is to employ a cylindrical magnet about seven inches long and the thickness of the finger (¾ inch), which is inserted in the supporting pillar of the Standard compass, a cylindrical hole being accurately bored for the purpose, but allowing a free movement for the magnet up and down.

† After crossing the magnetic equator, it may, in some cases, be desirable to remove the vertical magnet; and in high southern latitudes to place it in a reversed position, especially if there be much oscillation of the compass in bad weather.

How is the distance to be ascertained at which the vertical magnet ought to be placed below the compass?

A. Accurately by either of the two following methods, involving a short calculation; approximately, by methods that do not require calculation, which will be afterwards described :—

1. If we know $\mathfrak{D}$ λ μ; compute $\lambda\left(\mathfrak{D}+\frac{\mu}{\lambda}-1\right)\times$ tan dip, and find the angle of which it is the natural tangent. Then by trials made on shore, with the correcting magnet placed E. or W. of a compass and directed endwise to it, find the distance at which it produces a deviation equal to the last mentioned angle, then place the magnet at that distance below the compass.*

Or,

2. Compute the time in which ten vibrations made with a dipping needle in an east and west plane (or with its face to the north and south) shall equal ten vibrations similarly made on shore divided by a number equal to the square root of 1 — $\mathfrak{D}$ multiplied by λ,—*i.e.*, when

$$T' = \frac{T}{\sqrt{\lambda\,(1-\mathfrak{D})}}.$$

Place the ship's head E. or W. (magnetic), introduce the vertical magnet below the centre of the compass and move it up and down till the required time of ten vibrations (T') is obtained, then fix the magnet.†

If by any circumstances the ship's head cannot be placed on an E. or W. magnetic course, then, to correct on any other magnetic course, we must know g, and compute the ten vibrations to be observed for placing the correcting magnet by the formula $T' = \frac{T}{\sqrt{\lambda\,(1-\mathfrak{D}) + g\cot \text{dip}\,.\,\cos\zeta}}$.‡

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* *Example.*— *H.M.S. Achilles, Sheerness, October* 1863.

$$\lambda = .810,\quad \mathfrak{D}+\frac{\mu}{\lambda}-1 = .472,\quad \tan \text{dip} = 2.47$$

$$\text{required angle} = .810 \times .472 \times 2.47 = .944 = \text{nat. tan } \mathbf{43^\circ\ 20'}$$

† *Example.*— *H.M.S. Achilles, Sheerness, October* 1863.

$$\lambda = .810 \qquad 1-\mathfrak{D} = .879 \qquad T = 20.95 \text{ seconds}$$

$$\text{required time, } T' = \frac{20.95}{\sqrt{.810 \times .879}} = \frac{20.95}{.84} = \mathbf{25.0} \text{ seconds.}$$

‡ *Example.—H.M.S. Achilles, Sheerness, October* 1863. *Head S.* 26° *W. magnetic.*

$$\lambda = .810 \qquad 1-\mathfrak{D} = .879 \qquad T = 20.95 \text{ seconds.}$$

$$g = .196 \qquad \zeta = 206^\circ \qquad \cos\zeta = -.899 \qquad \cot.\text{ dip} = .400$$

$$\text{required time, } T' = \frac{20.95}{\sqrt{.712 + (.196 \times .400 \times -.899)}} = \frac{20.95}{\sqrt{.642}} = \mathbf{26.2} \text{ seconds.}$$

In the position of the Standard compass in most iron ships the following may be considered as approximate values when the quadrantal deviation has not been corrected :—

$$\left.\begin{array}{l}\lambda = .900\\ \mathfrak{D} = .100\end{array}\right\} \text{ or } \left\{\begin{array}{l}a = 0\\ e = -.190\end{array}\right.$$

Or,

$$\sqrt{\lambda(1-\mathfrak{D})} = \sqrt{1+e} = .9 = \frac{9}{10}$$

If the quadrantal deviation has been corrected by soft iron correctors of the usual shape, it will, by their deducting from e about $\frac{3}{4}$ths of its value and adding $\frac{1}{4}$th of its value to a, give

$$a = -.047$$
$$e = -.047$$

Or

$$\sqrt{1+e} = \sqrt{.953} = .976 = \frac{9\frac{3}{4}}{10}$$

So that we may nearly correct the heeling error of the Standard compass of an ordinary iron ship having its quadrantal deviation *uncorrected* by moving the vertical magnet under it till $T' = \frac{10}{9}T$, or till nine vibrations of the vertical dipping needle on board occupy the time of ten vibrations on shore.

Or,

if the quadrantal deviation has been corrected, then by moving the vertical magnet till $T' = \frac{10}{9\frac{3}{4}}T$, or till nine and three-quarter vibrations of the dipping needle on board occupy the time of ten on shore, or till 39 vibrations on board occupy the time of 40 on shore.

SECTION XII.

Advantages derived from a knowledge of the action of the compass on board ship.

Having now passed in review the several material points connected with the mariner's compass, and its action on board an iron ship, what advantages are derived by the navigator from the knowledge of the subject?

A. The advantages are manifold. The first and greatest is the additional security given to the navigation of the ship. There can be no doubt that many iron ships are lost or hazarded from the seaman not being prepared for, and not understanding changes which take place in the ship's magnetism—such changes, for instance, as arise from the heeling of the ship, from alteration of geographical position—more especially in high latitudes, from a change of course after the ship has sailed for a long time on one course—changes which are either not detected by one unacquainted with the subject, or which perplex and confound at some critical juncture, while by the navigator thoroughly instructed they would be looked for, understood, and provided against.

Other advantages are, that while familiarising the navigator with the several methods of adjustment by magnets, it furnishes him with means of testing and correcting the deviations without the loss of time required for the process of swinging the ship; and in new latitudes he is enabled either to readily readjust the magnets which correct his compass or the necessary tabular corrections.

Again, it teaches him where his Standard compass ought to be placed, and protects him from many errors not always harmless, but of a nature at times to cause expense and delay—such, for example, as that the effect of iron in the cargo may be prevented by the stowage of non-magnetic cargo above it; that the effect of iron in stanchions, or otherwise, is diminished by coating it with brass, canvas, paint, or other substances.*

*** Magnetism exerts its influence through all bodies, even the most dense—this is a remarkable property, which is not possessed by light, heat, or electricity.**

It further teaches him that fogs and other atmospherical conditions,* as also that the neighbourhood of the land,† have no appreciable effect on the compass.

Another advantage is, that it is a protection from what may be fairly called quack schemes for the correction of the deviation, of which there are many in the records of the Patent Office. Among such schemes, one especially may be mentioned which, from the frequency of being patented, must have a peculiar attraction to the uninstructed mind, *viz.*, the idea that by surrounding a compass by a non-conductor of electricity, of which gutta-percha is the favourite, the action of the iron of the ship on the compass may be intercepted.

Many considerations concur in showing the impossibility of such a force being interrupted by any substance whatever, but, one consideration is so simple that it is surprising it does not occur to the projector, namely, that if any such substance could intercept the magnetism of the ship, it would intercept the action of the earth on the needle, and so make the compass useless.

Another scheme which recently obtained some notoriety was for depolarizing or demagnetizing the hull of an iron ship by means of electric currents, and by rubbing the ship's sides and beams with electro-magnets in a direction reverse to the induced polarity. As might have been anticipated, the result of continual trials showed that it was impossible to destroy the magnetism of the general body of the ship, but that it is quite possible to magnetise the iron in the immediate neighbourhood of the compass so as to produce a powerful effect on the deviation, but more injurious than beneficial from its want of permanence.*

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* From this, of course, must be excepted the occasional effect of lightning in reversing the poles of the needle, or rendering it useless, numerous authenticated cases of which are on record as having affected the compasses of *wood-built* ships. The hull of an iron ship is, in the opinion of electricians, practically safe from lightning. So far as the writer is aware, there is no record of injury by lightning, either to an iron ship or her compasses.

[A curious electrical phenomenon affecting the compass needle can be produced by rubbing briskly the glass cover of the compass bowl with a silk or woollen cloth; the friction therefrom exciting an electrical condition in the glass sufficiently strong to cause a sensible deviation of the needle by attracting its ends, the deviation so produced remaining for some time, depending in duration on the electrical force excited. The attraction may be destroyed by moistening the surface of the glass. The foregoing facts were first noticed in the Philosophical Transactions for the year 1746.]

† The effect of volcanic or igneous rocks on a compass taken on shore and in close proximity to them is very perceptible. Sir James Ross, in his "Voyage of Research and Discovery to the Antarctic Regions," vol. i. p. 154, notes a case in point as occurring at the Auckland Islands, south of New Zealand. "As we passed Shoe Island at a distance of about fifty feet, the compasses were deviated nearly two points from their proper direction—showing in a striking manner the very extraordinary magnetic power of its component rock." Many other places are no doubt familiar to the navigators (St. Helena, for example), where, if a ship were equally close to the rocks, the compass would be similarly affected, but this is not in the sense of the seaman's belief as given in the text.

At present we may safely affirm "that the only way of destroying the effect of one magnetic disturbing force is, to introduce another magnetic disturbing agent whose force follows the same laws and has the same magnitude, but always acts in the opposite direction."†

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* See a paper "On the Amount and Changes of the Polar Magnetism at certain positions in H.M. iron-built and armour-plated ship Northumberland," in the Phil. Trans. of the Royal Society, 1868.

† Syllabus of a course of lectures on magnetical errors, compensations, and corrections, with special reference to iron ships and their compasses (Article 42) delivered to the Royal School of Naval Architecture, South Kensington Museum, in 1864 and 1870, by the Astronomer-Royal.

TERRESTRIAL MAGNETISM.

[From the construction of modern ships, wherein so large an amount of iron is introduced, the various causes which affect the mariner's compass become of importance in the art of navigation: no work, therefore, treating on compass deviations, can be considered complete without some account of the magnetism of the earth.

Terrestrial Magnetism is, however, a branch of science, embracing so vast a field both of observation and research, that little more can be given here than its general features, and confined even in this particular to those details which alone may be deemed necessary to the seaman.]

TERRESTRIAL MAGNETISM.

We are accustomed to speak of Terrestrial Magnetism, or the magnetic power of the Earth, as that force which causes a magnetic needle to point in a certain direction. It is a force which pervades the whole earth, and from whence the magnetic properties of every particle of iron entering into a ship's construction is derived. The object, therefore, of the science of Terrestrial Magnetism, so far as it is a science of observation, is to give us the means of determining, at any place and time, the direction and amount of that magnetic force.

The direction assumed by a freely suspended needle, in obedience to the earth's magnetism, is known as the line of force; but it is convenient, as will be hereafter seen, to refer the direction of the needle to two planes—the horizontal and the vertical—the former passing through the centre of the needle, and the latter passing through the centre of the needle and the *meridian* of the place. The angle formed by the needle with the horizontal plane is known as the inclination or dip, and that formed by the vertical plane passing through the needle and the magnetic meridian as the declination or variation of the needle.

The results of magnetic observations are conveniently represented graphically by systems of lines usually known as *isodynamic*, *isoclinal*, and *isogonic*, or as lines of equal Force, equal Dip, and equal horizontal direction or Variation. For some purposes, and particularly for estimating the effect of a disturbing force on the direction of the needle, it is convenient to use the lines of equal Horizontal force, instead of the lines of equal Total force. The charts accompanying this brief memoir, on which these several lines are denoted, may be considered to represent approximately for the present epoch (1870) the distribution of the following magnetic elements:

Total force, or that in the direction of the line of the dip.

Dip, or inclination of the needle.

Variation of the compass, or, as it is sometimes called, the declination of the needle.

Horizontal force (*i.e.*, the horizontal component of the Total force).

Lines of equal Total Force
(*in Absolute measure, British units*).

PLATE IV.

If we consider—which we may properly do—the magnetic action of the earth as being like that of a huge spherical magnet, at a considerable distance, its force, like that of an ordinary magnet, will be of different intensity and direction in different positions of the needle affected by it; one half its surface will have that magnetism which *attracts* the N. end of the needle, or *blue* magnetism,* and the other half will have that magnetism which repels the N. end of the needle, or *red* magnetism, and either force, whether repelling or attractive, will increase in intensity as we recede from the central or neutral dividing part and approach the magnet poles: the separating lines of these two magnetisms, or where the needle takes up a horizontal position, would be known as the magnetic equator, and at two points opposite, or nearly so, where the needle points vertically, would be the magnetic poles.

The distribution of these features on the earth's surface is shown on two spherical maps,† by a system of lines of equal values of the Total force coloured also to show the geographical limits of the red and blue magnetism. The magnetic equator—a term commonly employed to distinguish the region where the dip is 0—is shown by a thick line,‡ and the position of the two magnetic poles, or where the dip is 90°, by encircled dots.

One of the most striking features in the distribution of the earth's magnetic force, as shown by tracing out the lines of equal value, is, that the points of greatest intensity do not correspond with the magnetic poles. This has led to some confusion—these points having been occasionally designated as the magnetic poles; they are now usually and more conveniently known as magnetic foci, or regions of greatest magnetic force.

In the northern hemisphere there are two such regions, and theory points to there being two corresponding regions in the southern hemisphere. In the northern hemisphere, especially, these foci are of unequal strength—the strongest, or the American focus, is in 52° N., 90° W., and the weaker, or the Siberian focus, may be assumed as in 70° N. and 115° E. In the southern hemisphere, the position of the stronger focus may be assumed in 65° S. and 140° E., and the weaker focus in probably 50° S. and 130° E., being thus not far separated from each other, or from the magnetic pole.

At these foci the force is between two and three times the amount of that at the magnetic equator; or, more correctly, the earth's total force expressed in the scale in which British units are employed varies in these regions between 6·0 and 15·2.[*]

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* The convenience of distinguishing magnetic polarities by colour will be found referred to in the text, page 26.

† The projection employed embraces 227° of a great circle, or rather more than two-thirds of the sphere; a projection designed by Major-General Sir Henry James, Superintendent of the Ordnance Survey of Great Britain.

‡ The line connecting all the points on the earth's surface of least magnetic intensity is known as the dynamic equator: this line coincides more nearly with the magnetic or dip equator, than with the geographical equator.

The numerical values attached to the lines of equal Total force on the spherical maps are in *absolute* measure—a measure which is expressed in terms of a number multiplied by a time and by the square root of a weight, and divided by the square root of a length; the numerical value depending therefore on the units of time, weight, and length adopted. The unit of time adopted in all countries is the second; the units of length and weight adopted in British measure have usually been the foot and the grain, those adopted in foreign measures, the millimetre (=·03937 inch=·00328 foot), and the milligramme (·01543 grain).

To convert a numerical value obtained on the British system into the corresponding value obtained on the foreign system, the British number must therefore be multiplied by $\sqrt{\frac{\cdot 00328}{\cdot 01543}} = \cdot 46108$.[†]

No reliable methods have yet been devised for the measurement of the absolute total force; but the horizontal component admits of being determined with great accuracy on land, and the total force is then known by multiplying this horizontal force by the secant of the angle which the magnetic direction makes with the horizon, or, in other words, the dip of the needle.

The method devised by Gauss, an eminent German mathematician, for determining the absolute measure of the Horizontal force, is that now universally adopted; the principle is as follows. [‡]

A magnetic needle or bar of known dimensions and weight is suspended by a few fibres of silk, and the time of its vibrations, in a horizontal plane, on either side of the magnetic meridian, noted. These times of vibration are influenced by the magnetic force of the earth, and also by the greater or less magnetic force of the bar, and by its form and weight: the effect of the form and weight of the bar can be eliminated by simple and well-known rules for finding its moment of inertia. The magnetic force of the bar may be eliminated by finding its magnetic moment—this is done by suspending a magnetic needle in the magnetic meridian, and applying the original bar at measured distances perpendicular to it, and observing the angles of deflection produced on the suspended needle. The tangent of the deflections so produced are the measures of the *ratio* of the force exerted respectively by the magnet and the earth, and the *product* of the same two forces is known by the vibrations of the magnet, as the square of the number of vibrations in a given time is proportional to the product of the magnetic force of the earth and that of the bar.

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[*] "It is a remarkable fact that the magnetic force is greater in both the northern and southern hemispheres in the months of December, January, and February, when the sun is nearest the earth, than in those of May, June, and July, when he is more distant from it."—*Colonel Sabine's Presidential Address to British Association.* Belfast, 1852.

[†] The observed value of the absolute horizontal force at Greenwich for the present year (1870) is 3·85, and of the dip 68° 0′, from which we deduce the absolute values of the total force as 10·24, and the vertical force 9·51. In foreign measure they would respectively be 1·77, 4·72, and 4·38. In the earlier observations of the earth's magnetic force, as will be seen in maps of the time, the total force at London was considered as 1·372; the unit of this value was derived from a determination of Humboldt in northern Peru, where, on the magnetic equator, he found a point of minimum intensity. All determinations, till a system of absolute measure was adopted, were referred to this unit.

[‡] The student is referred to the Admiralty Manual of Scientific Enquiry—Article: Terrestrial Magnetism—by General Sir Edward Sabine, P.R.S., for a complete description of the instruments and methods employed for determining the magnetic force.

The ratio and product of the two forces being thus determined, the value of that of the earth's or the bar may be separately ascertained—the earth's force being independent of the individual properties of the magnet bar, whether with respect to its magnetism, form, or weight.

The *relative* values of the earth's magnetic force at different places is more simply measured by comparing the number of vibrations made in a given time by the same magnetic bar, the squares of the number of vibrations in a given time being proportioned to the force which brings it back to the position of equilibrium,—a law which may be compared to that of the vibrations of the pendulum made under the influence of gravity. But this method gives no *absolute* measure of the magnitude of the earth's force, nor is it indeed accurate if between the times of observation there has occurred any change in the magnetism of the needle or in the earth's force.[*]

The *relative* mode of obtaining the intensity is, however, extremely useful when the determinations in a limited region can be made with due precautions and referred to a base station, where an absolute determination has been effected; as a similar connection then exists between the relative and absolute measure of the earth's magnetic force as exists in the determination of the longitudes of places to which chronometric meridian distances have been measured, from a station the longitude of which has been settled absolutely by astronomical observations.

By the methods just described, the earth's magnetic force, combined with the dip and variation of the needle, has within the last half century been determined with much precision at places distributed over its whole accessible parts. Several regions have received special magnetic surveys; among these are, notably, many parts of continental Europe, Great Britain, British North America, including the locality of the stronger foci in the northern hemisphere—the coasts of the United States, British India, extending to the Eastern Archipelago; the province of Victoria, Australia; and notably, the Antarctic regions, in H.M. Ships Erebus and Terror, under Sir James Ross.

From these sources, from the determinations of fixed magnetic observatories now widely spread over the globe, and from the detached observations of scientific navigators of all nations, magnetic charts of a most reliable character can be constructed.

[*] The relative values of the earth's *total* force at two places can be determined by observing the times of vibration of an ordinary dipping needle, in the plane of the meridian; *i.e.*, in the line of the dip; and that of the earth's *horizontal* force, by observing the times of vibration of a horizontal needle.

In both cases the intensities of the magnetic forces are compared from the formula—

$$\frac{F}{F'} = \frac{n^2}{n'^2} = \frac{T'^2}{T^2}$$

Where n and n' are the number of vibrations in small arcs made by the same needle in different places, or T and T′ the times of a given number of vibrations, and F and F′ the intensities.

The observations made by vibrating the ordinary dipping needle do not admit of such accuracy as those made by the horizontal needle, especially when the latter admits of suspension by a fine silken fibre. The ordinary dipping needle is therefore now seldom employed.

An extremely ingenious and valuable instrument, devised chiefly for obtaining the intensity and dip at sea (Fox's Dip Circle), admits of the relative total force being determined with great accuracy by the application of weights and deflectors to the dipping needle. The methods of observing with this instrument are given in full detail in the Admiralty Manual of Scientific Enquiry—Article: Terrestrial Magnetism.

CHART I. *Lines of equal Dip (Inclination).*

The line of no dip, commonly known as the magnetic equator, will be traced generally in the neighbourhood of the equator, from whence the inclination of the needle to the horizon increases gradually to a point in either hemisphere where the needle stands vertical, or the dip is 90°. These points are, for convenience, called the magnetic poles.[*] The lines of equal north or + dip, or where the N. end of the needle is drawn *downwards*, are shown by continuous lines, and those of south or – dip, or where the N. end of the needle is pushed *upwards*, by broken lines.

[These two regions of north and south dips are also distinguished in the spherical maps of the Total force by the respective colours of the earth's magnetism producing this effect on the needle; *viz.*, *blue*, or south polar magnetism, attracting the N. end of the needle—*red*, or north polar magnetism, repelling the N. end of the needle.]

These lines have among themselves a general parallelism, and are thus, to a certain extent, analagous to the parallels of latitude; the term "magnetic latitude" is, therefore occasionally used to denote the position of an observer with reference to the magnetic dip. It will, however, be seen that the rate at which the dip increases, in going from the magnetic equator to the poles, is not the same as that at which the geographical latitude increases: the dip increases more rapidly in low latitudes and less rapidly in high latitudes: near the magnetic equator, for a degree of latitude, the dip increases about 2°, while, near the magnetic poles, it increases only about ½° for a degree of latitude.

The use of this chart to the navigator, with its table of natural tangents at the side, is sufficiently explained in the text, pages 85—8.

CHART II. *Lines of equal Horizontal force.*

Before describing this chart, it is desirable to repeat, that for many purposes, but more especially for navigation, it is found convenient, instead of considering the earth's magnetic force as a single force acting in the direction of the line of dip, to consider it as composed of two component parts: one, the horizontal force, which acts in a direction parallel to the surface of the earth, and towards the magnetic north at the place; and the other, the vertical force, acting in a direction perpendicular to the horizontal force; *downwards*, in the northern magnetic hemisphere, and *upwards* in the southern magnetic hemisphere.

The chart exhibiting the lines of equal horizontal force shows that this force, from being a maximum near the magnetic equator, diminishes as the magnetic poles are approached. This, as will be readily understood, arises, not from any diminution of the magnetic force of the earth, for that increases as we go to the poles, but from its direction becoming more and more inclined to the horizon. Hence the comparative sluggishness of the compass in high latitudes, and its uselessness in the neighbourhood of the magnetic poles.

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[*] The magnetic pole in the northern hemisphere was reached by Commander, afterwards Sir James Ross in 1831, during a voyage attempted for the discovery of the N.W. passage. The position of vertical dip (or 89° 59′) was then observed in 70° 5′ N., 96° 43′ W. The magnetic pole in the southern hemisphere was nearly attained by the same navigator in a voyage to the Antarctic regions for magnetical discovery and research made in H.M. Ships Erebus and Terror in 1839-43. From observations in the neighbourhood—the highest dip attained being 88° 56′—the position of vertical dip was considered to be in 73½° S. 147½° E.

The use of this chart to the navigator, with its table of the reciprocal of the horizontal force at the side, and the relative scale adopted, is sufficiently explained in the text, pages 30, 85-88.

CHART III. *Lines of equal Variation* (*Declination*).

It will be seen by the arrangement of these lines, notwithstanding the variety of their flexures, that the surface of the globe is, speaking generally, divided into two regions; one, the smaller, in which the variation is westerly, as indicated by the continuous lines—the other, and larger, in which the variation is easterly, as indicated by the broken lines. As a general rule, westerly variation prevails in the Atlantic Ocean —excepting part of the West Indies—and the Indian Ocean; easterly variation in the Pacific Ocean.

It will be further seen that these lines converge to that point in North America already described as the situation of the north magnetic pole, and this convergence further indicates that it is a true magnetic pole, *i.e.*, a place towards which the needle points in all the adjoining regions. There is a similar convergence to the point in the antarctic regions, southward of Australia, denoted as the south magnetic pole. If, however, we were to lay down these lines of equal variation on a chart of globular construction which comprised these poles, there would be a similar convergence of the lines to the north and south poles of the earth. This arises, not from the earth's poles being magnetic poles, but simply from these conditions, *viz.*, that if a needle were moved in a small circle round the terrestrial pole, the direction of the needle would remain unchanged, but the direction of the terrestrial meridian, and consequently the variation, would go through every angle from 0 to 360°.

The use of a Variation Chart to enable the navigator to shape his course in the ordinary practice of navigation is obvious, and were it confined to this, would require no further explanation; but there are two conditions connected with modern navigation, namely, the increased speed caused by the use of steam, and the introduction of iron-built ships, which give it a further usefulness.

For the first of these conditions it indicates those parts of the globe where the variation changes most rapidly, as shown by the lines being crowded together, and lying in a direction at right angles to the usual tracks of navigation: of these the most remarkable are the coasts of Newfoundland and North America, *the English Channel and its approach from the Westward.*

A vessel steaming from Cape Race, in Newfoundland, to Halifax, in Nova Scotia—a distance of 420 miles, and which therefore could easily be performed in 36 hours—changes the variation 10°; similarly, a fast steam vessel off Cape Clear, bound to Spithead—a distance of 360 miles, or a passage of 30 hours—would change the variation 5°. In both these examples the necessity of consulting a variation chart, and correcting the courses for changes of variation at short intervals of time, are evident.

To the second condition, and this is of great importance, it enables the navigator at any time, and at any place, to check his table of deviations by astronomical observations: as the simple difference between the variation as observed at his compass, and the variation, as shown by his chart, represents the amount of disturbance due to the iron of the ship, or the deviation of the compass.

It will have been observed that the magnetic elements given on the charts are approximately for the present time (1870). It will be understood by this, that their values are not permanent: each component is subject to a small amount of change, corresponding in period to the earth's revolution round the sun, and to its rotation round its own axis; and also to a change which takes place in the same direction, extending over long periods of time, and which, however slow the rate of change may be, attains a large value in the course of years. This latter change is known as the "secular;" and the annual and diurnal changes as "periodical."*

The periodic changes and irregular disturbances may be safely disregarded by the navigator; the secular change of the variation in some parts of the globe undergoes notable change in the course of a few years; for example, in the British islands, and the neighbouring seas, the annual decrease is from 7 to 8 minutes, and appears to be increasing. These annual changes in the value of the variation are, however, now generally given in charts of navigation.

The following facts are useful to seamen in relation to the earth's magnetism:—

The most violent storms of wind appear to be wholly without influence on the magnetometers employed in fixed observatories; and it has been further observed, that as with *wind* storms, so it is with *thunder* storms, which, even when close at hand, exercise no perceptible influence on the magnetic needle, unless the ship be actually struck by lightning, when sometimes the needles are demagnetized, or even have their magnetism reversed.

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* Besides these, the earth's magnetism is continually undergoing small shocks, which occur simultaneously over large portions of the globe, each component undergoing at the time small and irregular fluctuations; these are classed as "irregular" disturbances, and known when violent in degree as "magnetic storms."

USEFUL TABLES

EMPLOYED IN

CALCULATION OF CO-EFFICIENTS.

I.—TABLE OF THE PRODUCTS OF EVERY TENTH MINUTE OF ARC.

From 0° 0′ to 38° 50′,

MULTIPLIED BY THE SINES OF THE RHUMBS,

OR

S_1, S_2, S_3, S_4, S_5, S_6, and S_7.

S_1=Nat. sin. 11° 15′=·19509
S_2=Nat. sin. 22° 30′=·38268
S_3=Nat. sin. 33° 45′=·55557
S_4=Nat. sin. 45° 0′=·70710
S_5=Nat. sin. 56° 15′=·83147
S_6=Nat. sin. 67° 30′=·92388
S_7=Nat. sin. 78° 45′=·98078

(*This Table is used for the Calculation of the Co-efficients B, C, D, E.*)

II.—TABLE FOR COMPUTING THE PRODUCTS OF THE NUMBERS.

From ·001 to 1·000

BY THE SINES OF THE RHUMBS.

(*Useful for the Calculation of a Deviation Table from Co-efficients* 𝔅, ℭ, 𝔇, 𝔈.)

III.—TABLE OF NATURAL SINES, TANGENTS, ETC.

TABLE I.

PRODUCTS OF ARCS MULTIPLIED BY THE SINES OF THE RHUMBS.

ARCS.	S_1 (Sin. 11¼°).	S_2 (Sin. 22½°).	S_3 (Sin. 33¾°).	S_4 (Sin. 45°).	S_5 (Sin. 56¼°).	S_6 (Sin. 67½°).	S_7 (Sin. 78¾°).	ARCS.
° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′
0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0	0 0
0 10	0 2	0 4	0 6	0 7	0 8	0 9	0 10	0 10
0 20	0 4	0 8	0 11	0 14	0 17	0 18	0 20	0 20
0 30	0 6	0 11	0 17	0 21	0 25	0 28	0 29	0 30
0 40	0 8	0 15	0 22	0 28	0 33	0 37	0 39	0 40
0 50	0 10	0 19	0 28	0 35	0 42	0 46	0 50	0 50
1 0	0 12	0 23	0 33	0 42	0 50	0 55	0 59	1 0
1 10	0 14	0 27	0 39	0 49	0 58	1 5	1 9	1 10
1 20	0 16	0 31	0 44	0 57	1 7	1 14	1 18	1 20
1 30	0 18	0 34	0 50	1 4	1 15	1 23	1 28	1 30
1 40	0 20	0 38	0 56	1 11	1 23	1 32	1 38	1 40
1 50	0 22	0 42	1 1	1 18	1 32	1 42	1 48	1 50
2 0	0 23	0 46	1 7	1 25	1 40	1 51	1 58	2 0
2 10	0 25	0 50	1 12	1 32	1 48	2 0	2 8	2 10
2 20	0 27	0 54	1 18	1 39	1 56	2 9	2 17	2 20
2 30	0 29	0 57	1 23	1 46	2 5	2 19	2 27	2 30
2 40	0 31	1 1	1 29	1 53	2 13	2 28	2 37	2 40
2 50	0 33	1 5	1 34	2 0	2 21	2 37	2 47	2 50
3 0	0 35	1 9	1 40	2 7	2 30	2 46	2 57	3 0
3 10	0 37	1 13	1 46	2 14	2 38	2 56	3 6	3 10
3 20	0 39	1 17	1 51	2 21	2 46	3 5	3 16	3 20
3 30	0 41	1 20	1 57	2 29	2 55	3 14	3 26	3 30
3 40	0 43	1 24	2 2	2 36	3 3	3 23	3 36	3 40
3 50	0 45	1 28	2 8	2 43	3 11	3 33	3 46	3 50
4 0	0 47	1 32	2 13	2 50	3 20	3 42	3 55	4 0
4 10	0 49	1 36	2 19	2 57	3 28	3 51	4 5	4 10
4 20	0 51	1 40	2 24	3 4	3 36	4 0	4 15	4 20
4 30	0 53	1 43	2 30	3 11	3 45	4 10	4 25	4 30
4 40	0 55	1 47	2 36	3 18	3 53	4 19	4 35	4 40
4 50	0 57	1 51	2 41	3 25	4 1	4 28	4 44	4 50
5 0	0 59	1 55	2 47	3 32	4 9	4 37	4 54	5 0
5 10	1 1	1 59	2 52	3 39	4 18	4 46	5 4	5 10
5 20	1 2	2 3	2 58	3 46	4 26	4 56	5 14	5 20
5 30	1 4	2 6	3 3	3 53	4 34	5 5	5 24	5 30
5 40	1 6	2 10	3 9	4 0	4 43	5 14	5 34	5 40
5 50	1 8	2 14	3 14	4 8	4 51	5 23	5 43	5 50
6 0	1 10	2 18	3 20	4 15	4 59	5 33	5 53	6 0
6 10	1 12	2 22	3 26	4 22	5 8	5 42	6 3	6 10
6 20	1 14	2 25	3 31	4 29	5 16	5 51	6 13	6 20
6 30	1 16	2 29	3 37	4 36	5 24	6 0	6 23	6 30
6 40	1 18	2 33	3 42	4 43	5 33	6 10	6 32	6 40
6 50	1 20	2 37	3 48	4 50	5 41	6 19	6 42	6 50

TABLE I.—Products of Arcs

ARCS.	S_1 (Sin. 11¼°).	S_2 (Sin. 22½°).	S_3 (Sin. 33¾°).	S_4 (Sin. 45°).	S_5 (Sin. 56¼°).	S_6 (Sin. 67½°).	S_7 (Sin. 78¾°).	ARCS.
° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′
7 0	1 22	2 41	3 53	4 57	5 49	6 23	6 52	7 0
7 10	1 24	2 45	3 59	5 4	5 58	6 37	7 2	7 10
7 20	1 26	2 49	4 4	5 11	6 6	6 47	7 12	7 20
7 30	1 28	2 52	4 10	5 18	6 14	6 56	7 21	7 30
7 40	1 30	2 56	4 16	5 25	6 23	7 5	7 31	7 40
7 50	1 32	3 0	4 21	5 32	6 31	7 14	7 41	7 50
8 0	1 34	3 4	4 27	5 39	6 39	7 24	7 51	8 0
8 10	1 36	3 8	4 32	5 47	6 47	7 33	8 1	8 10
8 20	1 38	3 11	4 38	5 54	6 56	7 42	8 10	8 20
8 30	1 40	3 15	4 43	6 1	7 4	7 51	8 20	8 30
8 40	1 41	3 19	4 49	6 8	7 12	8 0	8 30	8 40
8 50	1 43	3 23	4 54	6 15	7 21	8 10	8 40	8 50
9 0	1 45	3 27	5 0	6 22	7 29	8 19	8 50	9 0
9 10	1 47	3 30	5 6	6 29	7 37	8 28	8 59	9 10
9 20	1 49	3 34	5 11	6 36	7 46	8 37	9 9	9 20
9 30	1 51	3 38	5 17	6 43	7 54	8 47	9 19	9 30
9 40	1 53	3 42	5 22	6 50	8 2	8 56	9 29	9 40
9 50	1 55	3 46	5 28	6 57	8 11	9 5	9 39	9 50
10 0	1 57	3 50	5 33	7 4	8 19	9 14	9 48	10 0
10 10	1 59	3 53	5 39	7 11	8 27	9 24	9 58	10 10
10 20	2 1	3 57	5 44	7 18	8 36	9 33	10 8	10 20
10 30	2 3	4 1	5 50	7 25	8 44	9 42	10 18	10 30
10 40	2 5	4 5	5 56	7 33	8 52	9 51	10 28	10 40
10 50	2 7	4 9	6 1	7 40	9 0	10 1	10 38	10 50
11 0	2 9	4 13	6 7	7 47	9 9	10 10	10 47	11 0
11 10	2 11	4 16	6 12	7 54	9 17	10 19	10 57	11 10
11 20	2 13	4 20	6 18	8 1	9 25	10 28	11 7	11 20
11 30	2 15	4 24	6 23	8 8	9 34	10 37	11 17	11 30
11 40	2 17	4 28	6 29	8 15	9 42	10 47	11 27	11 40
11 50	2 19	4 32	6 34	8 22	9 50	10 56	11 36	11 50
12 0	2 20	4 36	6 40	8 29	9 59	11 5	11 46	12 0
12 10	2 22	4 39	6 46	8 36	10 7	11 14	11 56	12 10
12 20	2 24	4 43	6 51	8 43	10 15	11 24	12 6	12 20
12 30	2 26	4 47	6 57	8 50	10 24	11 33	12 16	12 30
12 40	2 28	4 51	7 2	8 57	10 32	11 42	12 25	12 40
12 50	2 30	4 55	7 8	9 4	10 40	11 51	12 35	12 50
13 0	2 32	4 58	7 13	9 12	10 49	12 1	12 45	13 0
13 10	2 34	5 2	7 19	9 19	10 57	12 10	12 55	13 10
13 20	2 36	5 6	7 24	9 26	11 5	12 19	13 5	13 20
13 30	2 38	5 10	7 30	9 33	11 13	12 28	13 14	13 30
13 40	2 40	5 14	7 36	9 40	11 22	12 38	13 24	13 40
13 50	2 42	5 18	7 41	9 47	11 30	12 47	13 34	13 50
14 0	2 44	5 21	7 47	9 54	11 38	12 56	13 44	14 0
14 10	2 46	5 25	7 52	10 1	11 47	13 5	13 54	14 10
14 20	2 48	5 29	7 58	10 8	11 55	13 15	14 3	14 20
14 30	2 50	5 33	8 3	10 15	12 3	13 24	14 13	14 30
14 40	2 52	5 37	8 9	10 22	12 12	13 33	14 23	14 40
14 50	2 54	5 41	8 14	10 29	12 20	13 42	14 33	14 50

Multiplied by the Sines of the Rhumbs—(*continued*).

ARCS.	S_1 (Sin. 11¼°).	S_2 (Sin. 22½°).	S_3 (Sin. 33¾°).	S_4 (Sin. 45°).	S_5 (Sin. 56¼°).	S_6 (Sin. 67½°).	S_7 (Sin. 78¾°).	ARCS.
° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′
15 0	2 56	5 44	8 20	10 36	12 28	13 51	14 43	15 0
15 10	2 58	5 48	8 26	10 43	12 37	14 1	14 53	15 10
15 20	2 59	5 52	8 31	10 51	12 45	14 10	15 2	15 20
15 30	3 1	5 56	8 37	10 58	12 53	14 19	15 12	15 30
15 40	3 3	6 0	8 42	11 5	13 2	14 28	15 22	15 40
15 50	3 5	6 4	8 48	11 12	13 10	14 38	15 32	15 50
16 0	3 7	6 7	8 53	11 19	13 18	14 47	15 42	16 0
16 10	3 9	6 11	8 59	11 26	13 27	14 56	15 51	16 10
16 20	3 11	6 15	9 4	11 33	13 35	15 5	16 1	16 20
16 30	3 13	6 19	9 10	11 40	13 43	15 15	16 11	16 30
16 40	3 15	6 23	9 16	11 47	13 51	15 24	16 21	16 40
16 50	3 17	6 27	9 21	11 54	14 0	15 33	16 31	16 50
17 0	3 19	6 30	9 27	12 1	14 8	15 42	16 40	17 0
17 10	3 21	6 34	9 32	12 8	14 16	15 52	16 50	17 10
17 20	3 23	6 38	9 38	12 15	14 25	16 1	17 0	17 20
17 30	3 25	6 42	9 43	12 22	14 33	16 10	17 10	17 30
17 40	3 27	6 46	9 49	12 30	14 41	16 19	17 20	17 40
17 50	3 29	6 50	9 54	12 37	14 50	16 29	17 29	17 50
18 0	3 31	6 53	10 0	12 44	14 58	16 38	17 39	18 0
18 10	3 33	6 57	10 6	12 51	15 6	16 47	17 49	18 10
18 20	3 35	7 1	10 11	12 58	15 15	16 56	17 59	18 20
18 30	3 37	7 5	10 17	13 5	15 23	17 6	18 9	18 30
18 40	3 39	7 9	10 22	13 12	15 31	17 15	18 18	18 40
18 50	3 40	7 12	10 28	13 19	15 40	17 24	18 28	18 50
19 0	3 42	7 16	10 33	13 26	15 48	17 33	18 38	19 0
19 10	3 44	7 20	10 39	13 33	15 56	17 43	18 48	19 10
19 20	3 46	7 24	10 44	13 40	16 4	17 52	18 58	19 20
19 30	3 48	7 28	10 50	13 47	16 13	18 1	19 7	19 30
19 40	3 50	7 32	10 56	13 54	16 21	18 10	19 17	19 40
19 50	3 52	7 35	11 1	14 1	16 29	18 19	19 27	19 50
20 0	3 54	7 39	11 7	14 8	16 38	18 29	19 37	20 0
20 10	3 56	7 43	11 12	14 16	16 46	18 38	19 47	20 10
20 20	3 58	7 47	11 18	14 23	16 54	18 47	19 57	20 20
20 30	4 0	7 51	11 23	14 30	17 3	18 56	20 6	20 30
20 40	4 2	7 55	11 29	14 37	17 11	19 6	20 16	20 40
20 50	4 4	7 58	11 34	14 44	17 19	19 15	20 26	20 50
21 0	4 6	8 2	11 40	14 51	17 28	19 24	20 36	21 0
21 10	4 8	8 6	11 46	14 58	17 36	19 33	20 46	21 10
21 20	4 10	8 10	11 51	15 5	17 44	19 43	20 55	21 20
21 30	4 12	8 14	11 57	15 12	17 53	19 52	21 5	21 30
21 40	4 14	8 18	12 2	15 19	18 1	20 1	21 15	21 40
21 50	4 16	8 21	12 8	15 26	18 9	20 10	21 25	21 50
22 0	4 18	8 25	12 13	15 33	18 17	20 20	21 35	22 0
22 10	4 20	8 29	12 19	15 40	18 26	20 29	21 44	22 10
22 20	4 21	8 33	12 24	15 48	18 34	20 38	21 54	22 20
22 30	4 23	8 37	12 30	15 55	18 42	20 47	22 4	22 30
22 40	4 25	8 40	12 36	16 2	18 51	20 57	22 14	22 40
22 50	4 27	8 44	12 41	16 9	18 59	21 6	22 24	22 50

TABLE I.—Products of Arcs

ARCS.	S_1 (Sin. 11¼°).	S_2 (Sin. 22½°).	S_3 (Sin. 33¾°).	S_4 (Sin. 45°).	S_5 (Sin. 56¼°).	S_6 (Sin. 67½°).	S_7 (Sin. 78¾°).	ARCS.
° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′	° ′
23 0	4 29	8 48	12 47	16 16	19 7	21 15	22 33	23 0
23 10	4 31	8 52	12 52	16 23	19 16	21 24	22 43	23 10
23 20	4 33	8 56	12 58	16 30	19 24	21 33	22 53	23 20
23 30	4 35	9 0	13 3	16 37	19 32	21 43	23 5	23 30
23 40	4 37	9 3	13 9	16 44	19 41	21 52	23 13	23 40
23 50	4 39	9 7	13 14	16 51	19 49	22 1	23 22	23 50
24 0	4 41	9 11	13 20	16 58	19 58	22 10	23 32	24 0
24 10	4 42	9 15	13 26	17 6	20 6	22 20	23 42	24 10
24 20	4 44	9 18	13 32	17 12	20 14	22 28	23 52	24 20
24 30	4 46	9 22	13 36	17 20	20 22	22 38	24 2	24 30
24 40	4 48	9 26	13 42	17 26	20 30	22 48	24 12	24 40
24 50	4 50	9 30	13 48	17 34	20 40	22 56	24 22	24 50
25 0	4 52	9 34	13 54	17 40	20 48	23 6	24 32	25 0
25 10	4 54	9 38	14 0	17 48	20 56	23 16	24 40	25 10
25 20	4 56	9 42	14 4	17 54	21 4	23 24	24 50	25 20
25 30	4 58	9 46	14 10	18 2	21 12	23 34	25 0	25 30
25 40	5 0	9 50	14 16	18 8	21 20	23 42	25 10	25 40
25 50	5 2	9 53	14 20	18 16	21 30	23 52	25 20	25 50
26 0	5 4	9 56	14 26	18 24	21 38	24 2	25 30	26 0
26 10	5 6	10 0	14 32	18 30	21 46	24 10	25 40	26 10
26 20	5 8	10 4	14 38	18 38	21 54	24 20	25 50	26 20
26 30	5 10	10 8	14 44	18 44	22 2	24 28	26 0	26 30
26 40	5 12	10 12	14 48	18 52	22 10	24 38	26 10	26 40
26 50	5 14	10 16	14 54	18 58	22 18	24 48	26 20	26 50
27 0	5 16	10 20	15 0	19 6	22 26	24 56	26 28	27 0
27 10	5 18	10 24	15 6	19 12	22 36	25 6	26 38	27 10
27 20	5 20	10 28	15 12	19 20	22 44	25 16	26 48	27 20
27 30	5 22	10 32	15 16	19 26	22 52	25 24	26 58	27 30
27 40	5 24	10 36	15 22	19 34	23 0	25 34	27 8	27 40
27 50	5 26	10 40	15 28	19 40	23 8	25 44	27 18	27 50
28 0	5 28	10 42	15 34	19 48	23 16	25 52	27 28	28 0
28 10	5 30	10 46	15 38	19 54	23 24	26 2	27 38	28 10
28 20	5 32	10 50	15 44	20 2	23 34	26 10	27 48	28 20
28 30	5 34	10 54	15 50	20 10	23 42	26 20	27 58	28 30
28 40	5 36	10 58	15 56	20 16	23 50	26 30	28 6	28 40
28 50	5 38	11 2	16 0	20 24	23 58	26 38	28 16	28 50
29 0	5 40	11 6	16 6	20 30	24 6	26 48	28 26	29 0
29 10	5 42	11 10	16 12	20 38	24 14	26 56	28 36	29 10
29 20	5 44	11 14	16 18	20 44	24 26	27 6	28 46	29 20
29 30	5 46	11 18	16 24	20 52	24 32	27 14	28 56	29 30
29 40	5 48	11 22	16 28	20 58	24 40	27 24	29 6	29 40
29 50	5 50	11 24	16 34	21 6	24 48	27 34	29 16	29 50
30 0	5 52	11 28	16 40	21 12	24 56	27 42	29 26	30 0
30 10	5 54	11 32	16 46	21 20	25 4	27 52	29 36	30 10
30 20	5 56	11 36	16 52	21 26	25 14	28 2	29 46	30 20
30 30	5 58	11 40	16 56	21 34	25 22	28 10	29 56	30 30
30 40	5 59	11 44	17 2	21 42	25 30	28 20	30 4	30 40
30 50	6 0	11 48	17 8	21 48	25 38	28 28	30 14	30 50

Multiplied by the Sines of the Rhumbs—(*continued*).

Arcs.	S_1 (Sin. 11¼°).	S_2 (Sin. 22½°).	S_3 (Sin. 33¾°).	S_4 (Sin. 45°).	S_5 (Sin. 56¼°).	S_6 (Sin. 67½°).	S_7 (Sin. 78¾°).	**Arcs.**
31° 0′	6° 2′	11° 52′	17° 14′	21° 56′	25° 46′	28° 38′	30° 24′	**31° 0′**
31 10	6 4	11 56	17 20	22 2	25 56	28 48	30 34	**31 10**
31 20	6 6	12 0	17 24	22 10	26 4	28 56	30 44	**31 20**
31 30	6 8	12 4	17 30	22 16	26 12	29 6	30 54	**31 30**
31 40	6 10	12 8	17 36	22 24	26 20	29 16	31 4	**31 40**
31 50	6 12	12 12	17 40	22 30	26 28	29 24	31 14	**31 50**
32 0	6 14	12 14	17 46	22 38	26 36	29 34	31 24	**32 0**
32 10	6 16	12 18	17 52	22 44	26 44	29 42	31 34	**32 10**
32 20	6 18	12 22	17 58	22 52	26 52	29 52	31 42	**32 20**
32 30	6 20	12 26	18 4	22 58	27 2	30 2	31 52	**32 30**
32 40	6 22	12 30	18 8	23 6	27 10	30 10	32 2	**32 40**
32 50	6 24	12 34	18 14	23 12	27 18	30 20	32 12	**32 50**
33 0	6 26	12 38	18 20	23 20	27 26	30 30	32 22	**33 0**
33 10	6 28	12 42	18 26	23 28	27 34	30 38	32 32	**33 10**
33 20	6 30	12 46	18 32	23 34	27 42	30 48	32 42	**33 20**
33 30	6 32	12 50	18 36	23 42	27 50	30 58	32 52	**33 30**
33 40	6 34	12 54	18 42	23 48	28 0	31 6	33 2	**33 40**
33 50	6 36	12 56	18 48	23 56	28 8	31 16	33 10	**33 50**
34 0	6 38	13 0	18 54	24 2	28 16	31 24	33 20	**34 0**
34 10	6 40	13 4	19 0	24 10	28 24	31 34	33 30	**34 10**
34 20	6 42	13 8	19 4	24 16	28 32	31 44	33 40	**34 20**
34 30	6 44	13 12	19 10	24 24	28 40	31 52	33 50	**34 30**
34 40	6 46	13 16	19 16	24 30	28 50	32 1	34 0	**34 40**
34 50	6 48	13 20	19 20	24 38	28 58	32 10	34 10	**34 50**
35 0	6 50	13 24	19 26	24 44	29 6	32 20	34 20	**35 0**
35 10	6 52	13 28	19 32	24 52	29 14	32 30	34 30	**35 10**
35 20	6 54	13 32	19 38	25 0	29 22	32 38	34 40	**35 20**
35 30	6 56	13 36	19 44	25 6	29 30	32 48	34 50	**35 30**
35 40	6 58	13 40	19 48	25 14	29 40	32 58	34 58	**35 40**
35 50	7 0	13 44	19 54	25 20	29 48	33 6	35 8	**35 50**
36 0	7 2	13 46	20 0	25 28	29 56	33 16	35 18	**36 0**
36 10	7 4	13 50	20 6	25 34	30 4	33 24	35 28	**36 10**
36 20	7 6	13 54	20 12	25 42	30 12	33 34	35 33	**36 20**
36 30	7 8	13 58	20 16	25 48	30 20	33 44	35 48	**36 30**
36 40	7 10	14 2	20 22	25 56	30 30	33 52	35 58	**36 40**
36 50	7 12	14 6	20 28	26 2	30 38	34 2	36 8	**36 50**
37 0	7 14	14 10	20 34	26 10	30 46	34 12	36 18	**37 0**
37 10	7 16	14 14	20 40	26 16	30 54	34 20	36 28	**37 10**
37 20	7 18	14 18	20 44	26 24	31 2	34 30	36 36	**37 20**
37 30	7 20	14 20	20 50	26 32	31 12	34 40	36 46	**37 30**
37 40	7 21	14 24	20 56	26 38	31 20	34 48	36 56	**37 40**
37 50	7 22	14 28	21 0	26 46	31 28	34 58	37 6	**37 50**
38 0	7 24	14 32	21 6	26 52	31 36	35 6	37 16	**38 0**
38 10	7 26	14 36	21 12	27 0	31 44	35 16	37 26	**38 10**
38 20	7 28	14 40	21 18	27 6	31 52	35 26	37 36	**38 20**
38 30	7 30	14 44	21 22	27 14	32 0	35 34	37 46	**38 30**
38 40	7 32	14 48	21 28	27 20	32 8	35 44	37 56	**38 40**
38 50	7 34	14 52	21 34	27 28	32 16	35 52	38 6	**38 50**

II.—TABLE FOR COMPUTING THE PRODUCTS OF THE NUMBERS FROM ·001 TO 1·000 BY THE SINES OF THE RHUMBS.

(*This Table is useful for the Computation of a Deviation Table from the Co-efficients* 𝔅, ℭ, 𝔇, 𝔈.)

Numbers.	S_1 (Sin. 11¼° ·195).	S_2 (Sin. 22½° ·383).	S_3 (Sin. 33¾° ·556).	S_4 (Sin. 45° ·707).	S_5 (Siu. 56¼° ·831).	S_6 (Sin. 67½° ·924).	S_7 (Sin. 78¾° ·981).	Numbers.
·001	·000	·000	·001	·001	·001	·001	·001	·001
·002	·000	·001	·001	·001	·002	·002	·002	·002
·003	·001	·001	·002	·002	·003	·003	·003	·003
·004	·001	·002	·002	·003	·003	·004	·004	·004
·005	·001	·002	·003	·004	·004	·005	·005	·005
·006	·001	·002	·003	·004	·005	·006	·006	·006
·007	·001	·003	·004	·005	·006	·007	·007	·007
·008	·002	·003	·004	·006	·007	·007	·008	·002
·009	·002	·003	·006	·006	·007	·008	·009	·009
·01	·002	·004	·006	·007	·008	·009	·010	·01
·02	·004	·007	·011	·014	·017	·018	·020	·02
·03	·006	·011	·017	·021	·025	·028	·030	·03
·04	·008	·015	·022	·028	·033	·037	·039	·04
·05	·010	·019	·028	·035	·042	·046	·049	·05
·06	·012	·023	·033	·042	·050	·055	·059	·06
·07	·014	·027	·039	·049	·058	·065	·069	·07
·08	·016	·031	·044	·056	·066	·074	·078	·08
·09	·018	·034	·050	·063	·075	·083	·088	·09
·10	·020	·038	·055	·071	·083	·092	·098	·10
·11	·021	·042	·061	·078	·091	·102	·108	·11
·12	·023	·046	·067	·085	·100	·111	·118	·12
·13	·025	·050	·072	·092	·108	·120	·128	·13
·14	·027	·054	·078	·099	·116	·129	·137	·14
·15	·029	·057	·083	·106	·125	·139	·147	·15
·16	·031	·061	·089	·113	·133	·148	·157	·16
·17	·033	·065	·094	·120	·141	·157	·167	·17
·18	·035	·069	·100	·127	·150	·166	·177	·18
·19	·037	·073	·106	·134	·158	·176	·186	·19
·20	·039	·077	·111	·141	·166	·185	·196	·20
·21	·041	·080	·117	·148	·175	·194	·206	·21
·22	·043	·084	·122	·156	·183	·203	·216	·22
·23	·045	·088	·128	·163	·191	·212	·226	·23
·24	·047	·092	·133	·170	·200	·222	·235	·24
·25	·049	·096	·139	·177	·208	·231	·245	·25
·26	·051	·099	·144	·184	·216	·240	·255	·26
·27	·053	·103	·150	·191	·224	·249	·265	·27
·28	·055	·107	·156	·198	·233	·259	·275	·28
·29	·057	·111	·161	·205	·241	·268	·284	·29
·30	·059	·115	·167	·212	·250	·277	·294	·30

II.—Table for Computing Products of Numbers from ·001 to 1·000—(*continued*).

Numbers.	S_1 (Sin. 11¼″ ·195).	S_2 (Sin. 22½° 383).	S_3 (Sin. 33¾° ·556).	S_4 (Sin. 45° ·707).	S_5 (Sin. 56¼° ·831).	S_6 (Sin. 67½° ·924).	S_7 (Sin. 78¾° ·981).	Numbers.
·31	·060	·119	·172	·219	·258	·286	·304	**·31**
·32	·062	·122	·178	·226	·266	·296	·314	**·32**
·33	·064	·126	·183	·233	·274	·305	·324	**·33**
·34	·066	·130	·189	·240	·282	·314	·333	**·34**
·35	·068	·134	·194	·248	·291	·323	·343	**·35**
·36	·070	·138	·200	·255	·299	·333	·353	**·36**
·37	·072	·142	·206	·262	·308	·342	·363	**·37**
·38	·074	·145	·211	·269	·316	·351	·373	**·38**
·39	·076	·149	·217	·276	·324	·360	·383	**·39**
·40	·078	·153	·222	·283	·333	·370	·392	**·40**
·41	·080	·157	·228	·290	·341	·379	·402	**·41**
·42	·082	·161	·233	·297	·349	·388	·412	**·42**
·43	·084	·165	·239	·304	·358	·397	·422	**·43**
·44	·086	·168	·244	·311	·366	·407	·432	**·44**
·45	·088	·172	·250	·318	·374	·416	·441	**·45**
·46	·090	·176	·256	·325	·382	·425	·451	**·46**
·47	·092	·180	·261	·332	·391	·434	·461	**·47**
·48	·094	·184	·267	·339	·399	·443	·471	**·48**
·49	·096	·188	·272	·346	·407	·453	·481	**·49**
·50	·098	·191	·278	·354	·416	·462	·490	**·50**
·51	·100	·195	·283	·361	·424	·471	·500	**·51**
·52	·101	·199	·289	·368	·432	·480	·510	**·52**
·53	·103	·203	·294	·375	·441	·490	·520	**·53**
·54	·105	·207	·300	·382	·449	·499	·530	**·54**
·55	·107	·210	·305	·389	·457	·508	·539	**·55**
·56	·109	·214	·311	·396	·466	·517	·549	**·56**
·57	·111	·218	·317	·403	·474	·527	·559	**·57**
·58	·113	·222	·322	·410	·482	·536	·569	**·58**
·59	·115	·226	·328	·417	·491	·545	·579	**·59**
·60	·117	·230	·333	·424	·499	·554	·588	**·60**
·61	·119	·233	·339	·431	·507	·564	·598	**·61**
·62	·121	·237	·344	·438	·516	·573	·608	**·62**
·63	·123	·241	·350	·445	·524	·582	·618	**·63**
·64	·125	·245	·356	·453	·532	·591	·628	**·64**
·65	·127	·249	·361	·460	·540	·601	·638	**·65**
·66	·129	·253	·367	·467	·549	·610	·647	**·66**
·67	·131	·256	·372	·474	·557	·619	·657	**·67**
·68	·133	·260	·378	·481	·565	·628	·667	**·68**
·69	·135	·264	·383	·488	·574	·637	·677	**·69**
·70	·137	·268	·389	·495	·582	·647	·687	**·70**
·71	·139	·272	·394	·502	·590	·656	·696	**·71**
·72	·140	·276	·400	·509	·599	·665	·706	**·72**
·73	·142	·279	·406	·516	·607	·674	·716	**·73**
·74	·144	·283	·411	·523	·615	·684	·726	**·74**
·75	·146	·287	·417	·530	·624	·693	·736	**·75**

II.—Table for Computing Products of Numbers from ·001 to 1·000—(*continued.*)

Numbers.	S_1 (Sin. 11¼° ·195).	S_2 (Sin. 22½° ·383).	S_3 (Sin. 33¾° ·556).	S_4 (Sin. 45° ·707).	S_5 (Sin. 56¼° ·831).	S_6 (Sin. 67½° ·924).	S_7 (Sin. 78¾° ·981).	Numbers.
·76	·148	·291	·422	·537	·632	·702	·745	·76
·77	·150	·295	·428	·544	·640	·711	·755	·77
·78	·152	·298	·433	·552	·649	·721	·765	·78
·79	·154	·302	·439	·559	·657	·730	·775	·79
·80	·156	·306	·444	·566	·665	·739	·785	·80
·81	·158	·310	·450	·573	·673	·748	·794	·81
·82	·160	·314	·456	·580	·682	·758	·804	·82
·83	·162	·318	·461	·587	·690	·767	·814	·83
·84	·164	·321	·467	·594	·698	·776	·824	·84
·85	·166	·325	·472	·601	·707	·785	·834	·85
·86	·168	·329	·478	·608	·715	·795	·843	·86
·87	·170	·333	·483	·615	·723	·804	·853	·87
·88	·172	·337	·489	·622	·732	·813	·863	·88
·89	·174	·341	·494	·629	·740	·822	·873	·89
·90	·176	·344	·500	·636	·748	·831	·883	·90
·91	·178	·348	·506	·643	·757	·840	·893	·91
·92	·179	·352	·511	·651	·765	·850	·902	·92
·93	·181	·356	·517	·658	·773	·859	·912	·93
·94	·183	·360	·522	·665	·782	·868	·922	·94
·95	·185	·364	·528	·672	·790	·878	·932	·95
·96	·187	·367	·533	·679	·798	·887	·942	·96
·97	·189	·371	·539	·686	·807	·896	·951	·97
·98	·191	·375	·544	·693	·815	·905	·961	·98
·99	·193	·379	·550	·700	·823	·915	·971	·99
1·00	·195	·383	·556	·707	·831	·924	·981	1·00

III.—TABLE OF NATURAL SINES, TANGENTS, ETC.

Angle.	Sine.	Diff. for 10′.	Arc.	Tangent.	Cotan.	Versin.	Cosine.	— —
0°	·0000		·0000	·0000	infinite	·0000	1·0000	90°
1	·0175		·0175	·0175	57·290	·0002	·9998	89
2	·0349		·0349	·0349	28·636	·0006	·9994	88
3	·0523		·0524	·0524	19·081	·0014	·9986	87
4	·0698		·0698	·0700	14·301	·0024	·9976	86
5	·0872	·0029	·0873	·0875	11·430	·0038	·9962	85
6	·1045		·1047	·1051	9·514	·0055	·9945	84
7	·1219		·1222	·1228	8·144	·0075	·9925	83
8	·1392		·1396	·1405	7·115	·0097	·9903	82
9	·1564		·1571	·1584	6·314	·0123	·9877	81
10	·1736		·1745	·1763	5·671	·0152	·9848	80
11	·1908		·1920	·1944	5·145	·0184	·9816	79
12	·2079		·2094	·2126	4·705	·0219	·9781	78
13	·2250		·2269	·2309	4·331	·0256	·9744	77
14	·2419		·2443	·2493	4·011	·0297	·9703	76
15	·2588		·2618	·2679	3·732	·0341	·9659	75
16	·2756	·0028	·2793	·2867	3·487	·0387	·9613	74
17	·2924		·2967	·3057	3·271	·0437	·9563	73
18	·3090		·3142	·3249	3·078	·0489	·9511	72
19	·3256		·3316	·3443	2·904	·0545	·9455	71
20	·3420		·3491	·3640	2·747	·0603	·9397	70
21	·3584		·3665	·3839	2·605	·0664	·9336	69
22	·3746	·0027	·3840	·4040	2·475	·0728	·9272	68
23	·3907		·4014	·4245	2·356	·0795	·9205	67
24	·4067		·4189	·4452	2·246	·0865	·9135	66
25	·4226		·4363	·4663	2·145	·0937	·9063	65
26	·4384		·4538	·4877	2·050	·1012	·8988	64
27	·4540	·0026	·4712	·5095	1·963	·1090	·8910	63
28	·4695		·4887	·5317	1·881	·1171	·8829	62
29	·4848		·5061	·5543	1·804	·1254	·8746	61
30	·5000		·5236	·5774	1·732	·1340	·8660	60
31	·5150	·0025	·5411	·6009	1·664	·1428	·8572	59
32	·5299		·5585	·6249	1·600	·1520	·8480	58
33	·5446		·5760	·6494	1·540	·1613	·8387	57
34	·5592	·0024	·5934	·6745	1·483	·1710	·8290	56
35	·5736		·6109	·7002	1·428	·1808	·8192	55
36	·5878		·6283	·7265	1·376	·1910	·8090	54
37	·6018	·0023	·6458	·7536	1·327	·2014	·7986	53
38	·6157		·6632	·7813	1·280	·2120	·7880	52
39	·6293		·6807	·8098	1·235	·2229	·7771	51
40	·6428	·0022	·6981	·8391	1·192	·2340	·7660	50
41	·6561		·7156	·8693	1·150	·2453	·7547	49
42	·6691		·7330	·9004	1·111	·2569	·7431	48
43	·6820	·0021	·7505	·9325	1·072	·2686	·7314	47
44	·6947		·7679	·9657	1·036	·2807	·7193	46
45	·7071		·7854	1·0000	1·000	·2929	·7071	45
— —	Cosine.	Diff. for 10′.	—	Cotan.	Tangent.	—	Sine.	Angle.

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Plate IV.

THE EARTH'S MA

as shown by the distribution of lin
in Absolute measure (British units); the po
Equator; with the regions of blue
(Approximately for

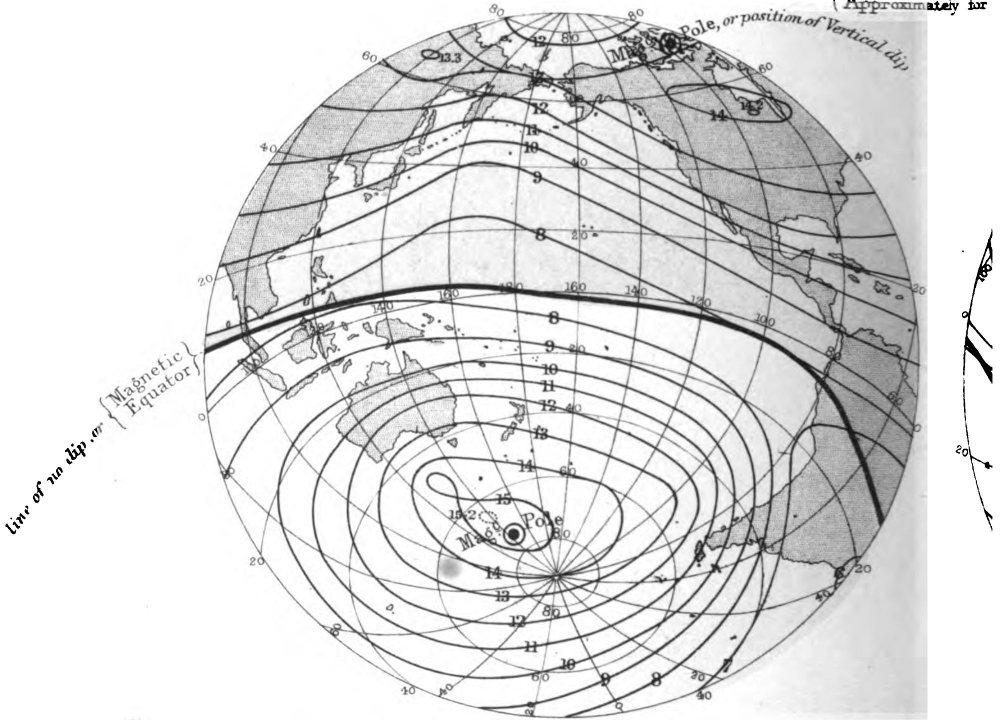
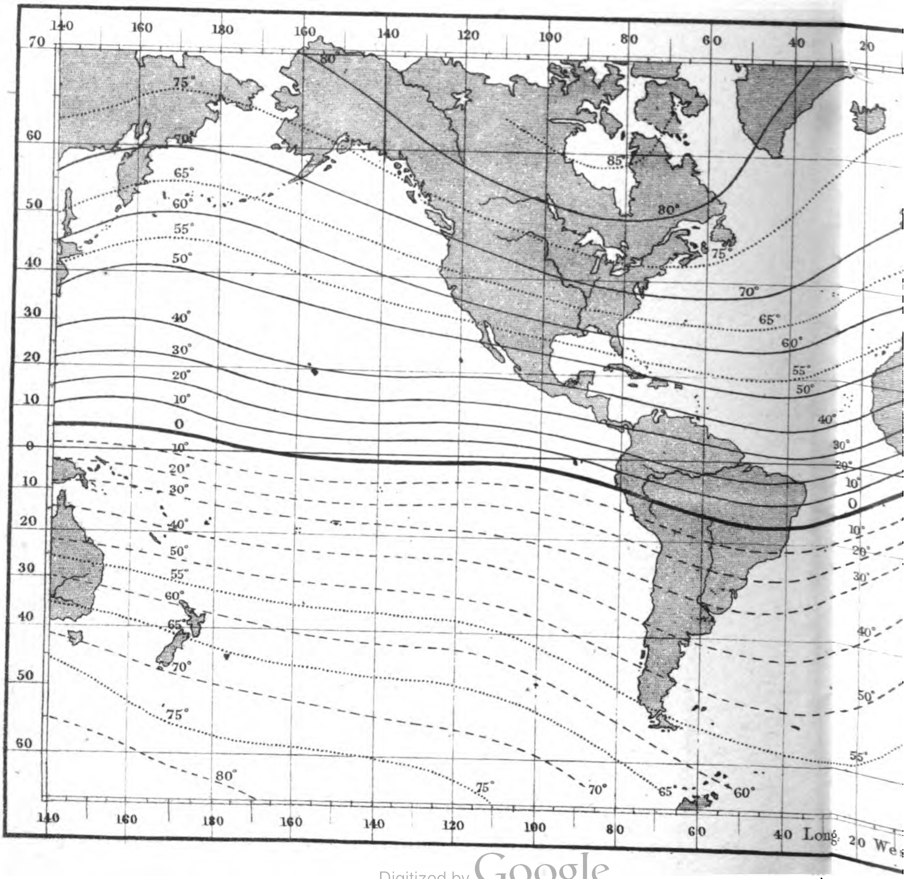
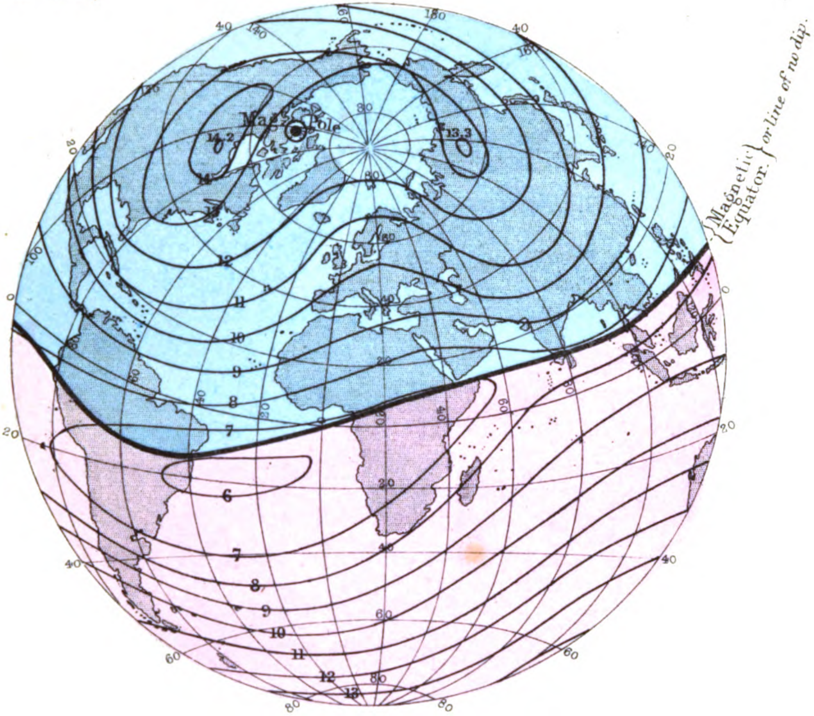

Mag. Pole, or position of Vertical dip
line of no dip, or {Magnetic Equator}
Mag. Pole
13.3
14.2
15.2
15
14
13
12
11
10
9
8
7
80
60
40
20
0
180
160
140
120
100

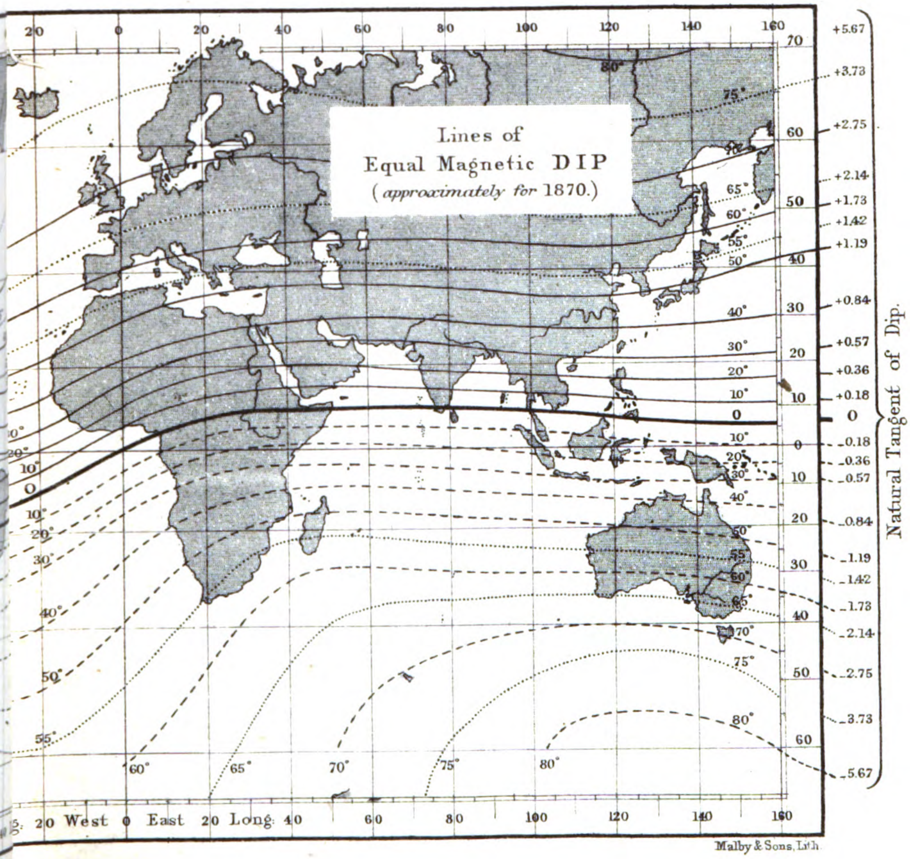
Chart I.



MAGNETISM

of lines of equal Total force,
e position of the Magnetic poles and
blue and red magnetism.
ly for 1870.)

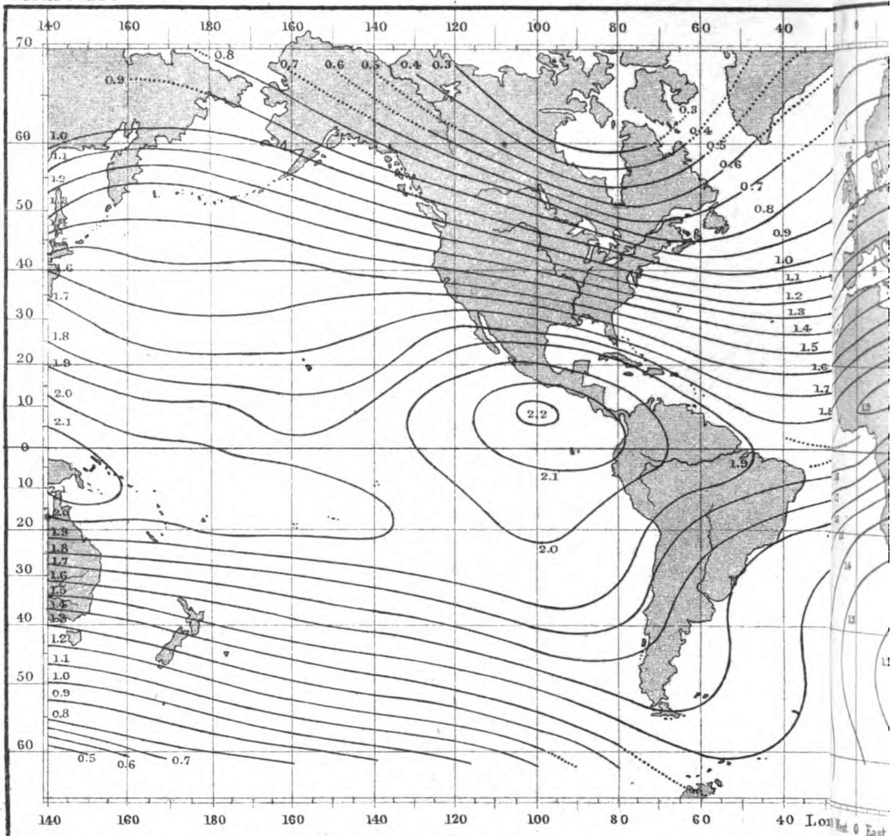




Lines of
Equal Magnetic DIP
(*approximately for* 1870.)

Malby & Sons, Lith.

Chart II.



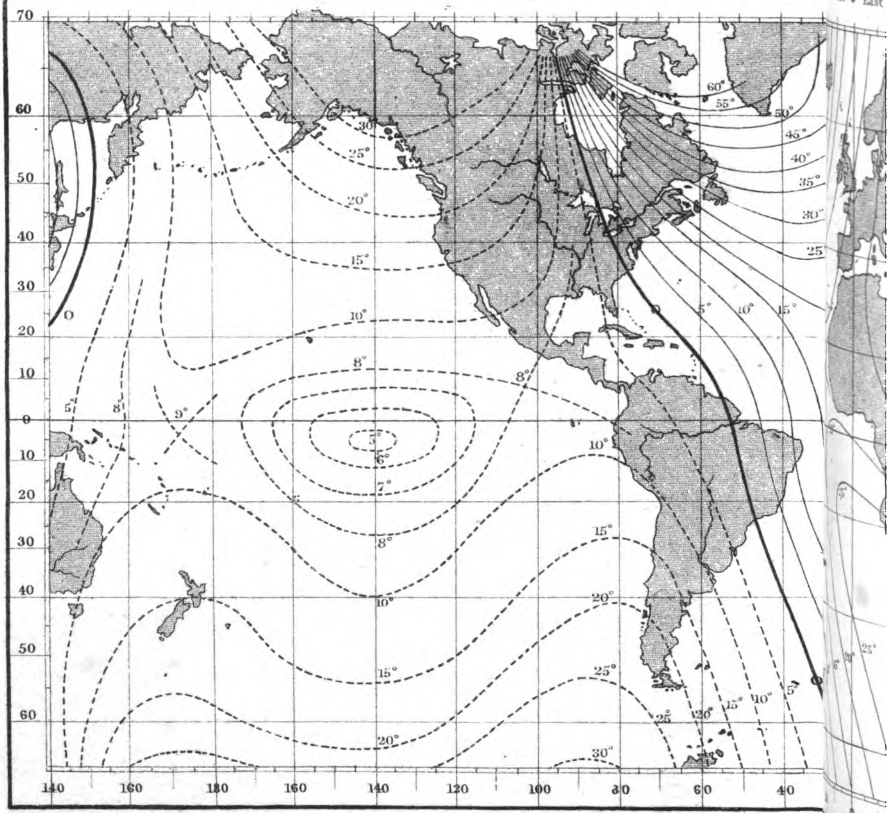
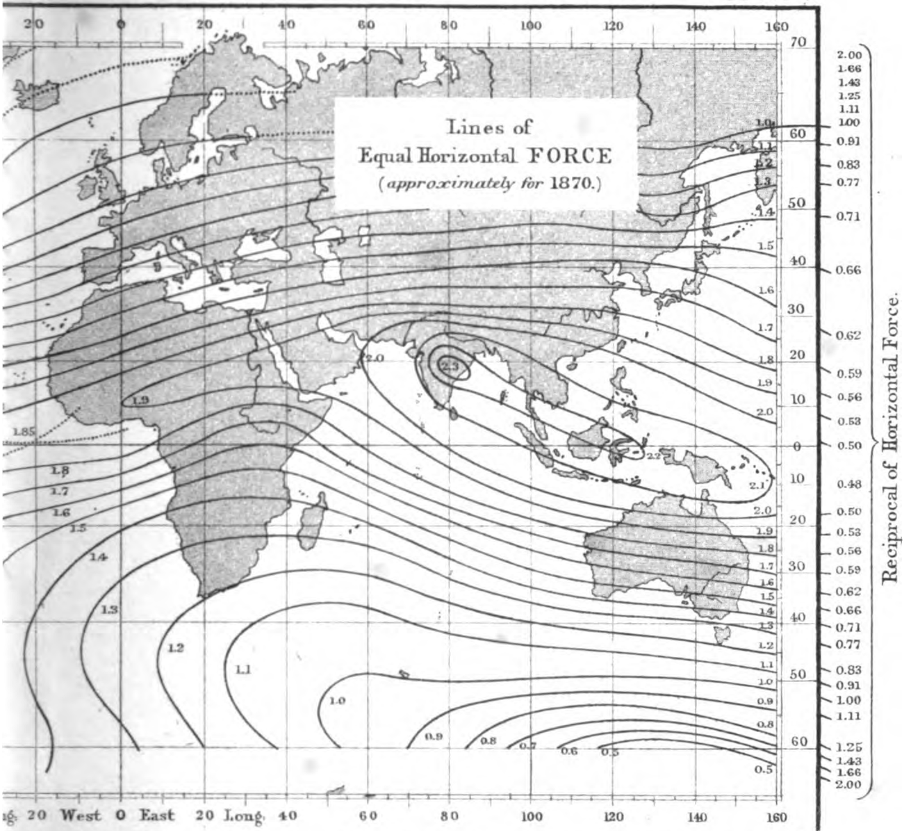
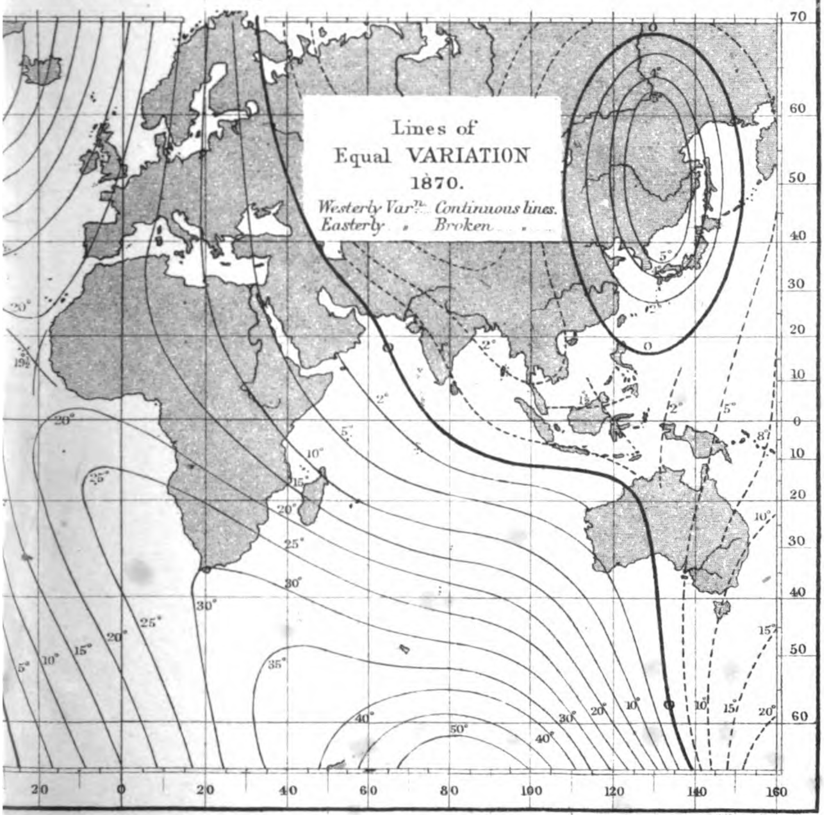


Chart III.

Plate V.



Lines of
Equal Horizontal FORCE
(*approximately for* 1870.)



Lines of
Equal VARIATION
1870.
Westerly Varⁿ. Continuous lines.
Easterly " Broken "

Malby & Sons, Lith.